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# UTILIZATION OF ACCEPTANCE DATA IN A DESCRIPTIVE MODEL FOR DETERMINING MAN'S ROLE IN A SYSTEM

*by Harold E. Price, Ewart E. Smith,*
*and Richard A. Behan*

Prepared under Contract No. NAS2-1346 *by*
SERENDIPITY ASSOCIATES
Sherman Oaks, Calif.
*for*

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SUMMARY

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This report contains the following information for use in the design of man-machine systems.

1. A partial descriptive model of the system development processes, for use in determining if man should be a system component, and if so what his optimal role and location should be. The model is presented in functional-flow-logic, with the concepts and methods explained in the text.

2. The problem of system inefficiency due to non-acceptance by man of his role is analyzed. Principles for avoiding acceptance problems are described, as well as methods for measuring acceptance factors.

3. An appendix is included, where some of the data on human capabilities and limitations is organized and presented in a manner consistent with the model utilization and the requirements-oriented system designer.

Author

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# I. INTRODUCTION

The lack of an adequate methodology for performing functions allocation became apparent earlier on this contract during a study of user acceptance as a criteria in system design. Specifically the study was concerned with pilot acceptance factors in the development of all-weather landing systems. The original intent was to (1) determine system performance acceptance factors, (2) recapitulate the man-machine system development process, which typically occurs without consideration of acceptance, and (3) indicate where in this typical man-machine system development process acceptance data should be considered. In attempting to recapitulate the man-machine system development process, it became apparent that there was no typical man-machine system development process. There was, in fact, no formal or widely accepted process at all. A brief investigation of the literature concerned with the general topic of man-machine system design and functions allocation in particular revealed that other investigators have arrived at the same conclusions.

In a document (95) entitled Factors Affecting Degree of Automation in Test and Checkout Equipment, which, among other things, reviews the problems of allocation of functions, Swain and Wohl assert:

> A rather stark conclusion emerges: There is no adequate systematic methodology in existence for allocating functions (in this case, test and checkout functions) between man and machine. This lack, in fact, is probably the central problem in human factors engineering today . . . . It is interesting to note that ten years of research and applications experience have failed to bring us closer to our goal than did the landmark article by Fitts in 1951 (p. 9).

In an article (52) in the Journal of Applied Psychology entitled Allocation of Functions Between Man and Machines in Automated Systems, Jordan discusses current problems and efforts to allocate functions between men and machines and arrives at a similar conclusion to Swain and Wohl. Jordan's final conclusion is stated as follows: "Herein lies the main future challenge to human factors engineering." (p. 165).

Jordan also presents an analogy in the physical sciences concerned with the concept of "ether" which

> . . . . played a central role in physical thinking for over a century after having first been introduced as a necessary medium for propagating electromagnetic waves. But during all this time all attempts to build and expand upon this concept led to difficulties and contradictions. A century of research on ether turned out to be sterile in that no significant advance was made during that time.

The conclusion which Jordan draws from this analogy is as follows:

> The lesson to be learned from this momentus episode is that when a scientific discipline finds itself in a dead end, despite hard and diligent work, the dead end should probably not be attributed to a lack of knowledge of facts, but to the use of faulty concepts which do not enable the discipline to order the facts properly. The failure of human factor engineering to advance in the area of allocation of functions seems to be such a situation . . . .

We wholeheartedlv agree that the problem is not entirely a lack of facts, but rather the ability to use these facts. Specifically we believe that this implies a need for a study of the requirements for allocation of functions. The study should be oriented toward the broader problems of the requirements for determining human performance in systems. To our knowledge, no one has tackled the problem from a requirements point of view, and attempted to analyze it into its components. Rather most attempts have been to assert in broad terms what man should do and what machines should do in systems. Furthermore, most philosophies today seem to imply that the allocation of functions to men and machines is a human factors problem. We do not believe this to be true. We do believe that human factors groups, or groups concerned with man-machine integration in systems, should have and apply a systematic method for determining optimum manned design solutions to system problems. It is the task of those groups charged with the responsibility for system development to allocate functions between men and machines. Presumably some human factors personnel will be involved.

The problem of allocating functions in man-machine systems resolves itself into three related problems:

1. A method for deriving and presenting the data appropriate to a given system development effort.
2. A method for organizing available data to facilitate their use in the system development effort.
3. A method which will pinpoint data scarce areas, to facilitate the management and direction of research programs.

The first problem is illustrated by the fact that frequently a system concept is made much too specific too soon in the process of system development. While this is partly a function of the confusion of design objectives at different levels of abstraction, it could be avoided if a more systematic approach were taken to system development efforts, particularly at the advanced development phase. An example in point is the present ILS autopilot coupler, which was designed and installed for use in landings in poor weather. But bad weather is exactly the time that it is not used. The coupler was not designed to fit into the man-machine system complex in which it is to be used. Use of the coupler is incompatible with time constraints, competing tasks, radar vectoring, etc. (91).

The second problem is pointed up by the fact that the majority of data manuals are organized according to academic subject matter specialties. While this may be satisfactory for instructional purposes, experience has shown that it is not an optimum organization for human factors personnel. A model of the functions allocation process would dictate a more efficient organization for available data.

The third problem is illustrated by the fact that research requirements more or less happen. A problem comes up and the answer is needed yesterday. The difficulty of managing a research program in such an environment is compounded when the time periods for system development are short. An adequate model for functions allocation would allow one to anticipate areas of needed research. Thus, the research manager would be in a position to anticipate further needs. The research program could then, in part, be designed to meet future data needs.

This report describes an initial attempt to develop a descriptive model of the requirements and constraints for determining optimal human performance in systems. It is important to note the use of the term descriptive model. A mathematical model for man-machine system design cannot be developed at this time for many reasons, not the least of which is the inability to quantify many human performance variables. However, this fact is no reason consideration of these, and other variables explicit in man-machine system design, cannot be systematically organized for consideration in man-machine system development. Further, until a descriptive model is developed a mathematical model cannot be developed, as we do not know the variables and relationships that have to be expressed mathematically. The descriptive model is oriented toward requirements and not means. As in any other system development it is necessary first to establish what must be done, and then to consider how to do it. This is not to say that the model does not consider existing concepts and techniques for performing man-machine system analysis and design. Rather, the attempt is to integrate existing concepts and techniques into the model development. It is believed that, just as is true with factual data, many concepts and techniques which are useful do exist but they have never been related in a systematic fashion.

## II. CONCEPTS AND ASSUMPTIONS

Certain concepts and assumptions are essential to the present program, and a brief discussion of them is presented here.

### Some Basic System Concepts

Since the word system is used so liberally in technical development, three basic concepts of systems are presented first. The concepts of development and operational systems; prime and maintenance systems; and local and remote systems are defined.

Development and operational systems. - Operational systems are to be differentiated from development systems because generalized designs which are useful for operational systems are different from generalized designs which are useful for development systems. An operational system is one which has been subjected to design and development, and for which means have been produced and assembled so that a required total system output can be obtained. Operational systems are "installed" or "assembled" systems capable of a specific over-all performance output with a given operational reliability. Some examples of operational systems are: oil refineries, Project Mercury, telephone communication systems, the X-15, etc.

A development system is one which is bounded on the input side by policy requirements for a system, and which is bounded on the output side by the assembled means capable of providing the operational performance required by the user. Thus, a development system provides as its output all of the individual means which satisfy a design solution for the system required by the policy. These means are assembled into an operational system capable of providing that output specified in the policy requirements. Development systems include within their boundaries such activities as: design of the operational system, development of a prototype of the operational system, production of the items that will be assembled to make up an operational system, assembly and installation of individual systems, and test and evaluation. As shown in Figure 1, development systems and operational systems are always adjacent systems. The output of a development system is always an input to an operational system, although operational systems require other inputs once they are installed or assembled.

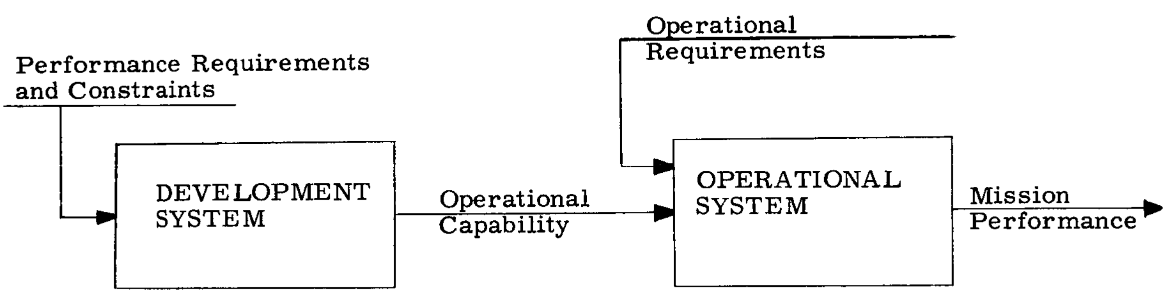



Figure 1. The development and operational systems.

The important point is that development systems can be deliberately organized and designed for efficiency of operation. The reader should differentiate between design of an operational system which is ordinarily a group of major efforts within the development system and <u>design of the development system itself</u> which must be accomplished prior to use of the development system. Design of a development system costs money. When the output is a complex operational system it may cost a great deal of money. Therefore, the expenditure of funds for designing a development system must be justified. Such expenditure can be justified when many copies of a given operational system must be produced as an output of a development system, or when many associated contractors are involved in the development of a complex system. The deliberate design of a development system can also be justified when the operational system to be produced must be an ultrahigh reliability system even though only a few copies must be produced. An example of an ultrahigh reliability system would be a Mars exploration system. For such a system, operational reliability approaching 1.00 may be so important that we may be willing to spend many dollars to arrive at an optimum design solution for the development system, to insure that the ultrahigh reliability operational system will meet its objectives.

Prime and maintenance systems. - A prime system is ordinarily a group of subsystems of a complete system. A prime system is composed of all of the means directly required to obtain the output performance required of the system, disregarding over-all operational reliability. Commonly, all of the units within a prime system will be critical with respect to the over-all system output. Therefore, in order to determine whether or not a specific unit belongs within the prime system, one may ask whether or not it is possible to obtain the output required of the system (without respect to operational reliability) if the unit in question is deleted from the system. If the output can be obtained without the unit, it is not part of the prime system. If the system is a man-machine system, it will be necessary to ask this question about units which are implemented by means of personnel action, as well as for units employing hardware means.

Thus, a prime system is composed of all of the units within the system boundary that are essential to total system performance capability, in that deletion of any prime unit will necessarily cause total system failure. Note that this definition may include "support" equipment or units within the prime system if the support units are essential with respect to total system output. The notation "support equipment" is often misleading, because it tends to belittle the role of the equipment so labeled. If a ground power plant of an aerospace system is essential, its failure has the same effect on total system performance as the failure of any other unit in the prime system.

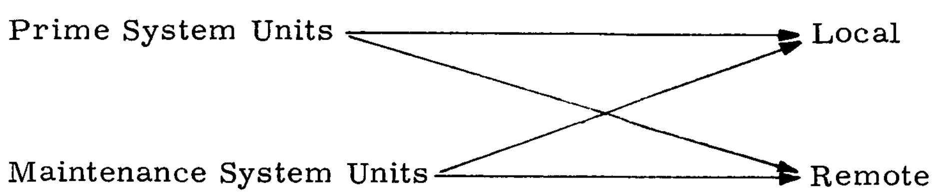
In order to achieve high operational reliability most complex systems employ maintenance systems in addition to prime systems. This is done because (1) most complex prime systems will not provide the total system output required over long periods of time without failure, even when the most reliable component means are employed, or (2) "single shot" or "one time" systems require exhaustive checkout and support before they can be operated.

Maintenance systems can thus be defined by stating that the outputs are repaired, replaced, verified, or adjusted units of the prime system, and that the critical input to the maintenance system is a signal that the prime system is out-of-tolerance, or information about the empirical rate of failure of units in the prime system. Perhaps a better way to define maintenance system outputs is to say that the output is sustained prime system performance capability--and maintenance systems might, therefore, be called "sustaining" systems.

The concept of prime and maintenance systems as used here refers to a way of dichotomizing an entire system. Prime and maintenance systems can also be visualized as "multiplicative" or "additive" systems respectively. This concept, to be discussed later, is somewhat more useful as it can be applied to either performances or physical means (personnel and hardware) at the system, subsystem, function or component, task or part level.

Local and remote systems. - Systems may also be described in terms of the geographical or physical location of the performance units within the total system configuration. It is frequently useful to describe systems, or for that matter any performance units, in terms of whether they are local or remote. Local refers to the immediate mission environment in which the system operates. Remote refers to some geographical or physical location away from the immediate mission environment. Remote systems or performance units also have two further qualifications, as follows: (1) Human beings may always participate in systems at the remote locations. They may have to be protected and sustained from any hostile environment. (2) Remote systems or performance units require some type of mechanization to permit their interaction with equipment and/or personnel of the local system.

Prime or maintenance systems can be either local or remote. That is, some aspects of prime performance may be local and some may be remote. Similarly, some aspects of maintenance performance may be local and some may be remote as illustrated below.




It is important that this concept is recognized as the term automation is frequently and incorrectly used to identify what is essentially remote control. In many systems which are considered automated systems the human operator is still in the loop of the primary system, but he is located remotely from the immediate mission environment. Even systems which are completely automated always require human participation to initiate system operation and to verify or utilize the system output.

The fact that remote systems are physically removed from local systems does not imply great distances. For example, in a system designed to handle radioactive materials the operator is in a remote location which may be only a matter of ten or fifteen feet from the actual location of the radioactive material. In other systems such as manned spacecraft many primary and maintenance system activities are carried on remotely from the vehicle itself and this distance may vary from a matter of feet (when the vehicle is on the launch pad) to hundreds or even thousands of miles when the vehicle is in flight.

The development process. - The sequence of developing a system in response to a set of requirements and constraints has been characterized in many ways. The concept we propose is not solely concerned with the development sequence, but with the development process as well. The development process consists of both vertical development (development of detail) and lateral development (development of scope). This is characterized by the matrix in Figure 2. Each cell of the matrix (as well as cell interactions) must be considered before the development process is complete for any system. Many exploratory or experimental systems will have a minimum of lateral developments, i.e., there will be no replications except possibly at the function or task level. The principal efforts of this program are concerned with requirements for development of detail, although development of scope is treated as appropriate.

Lateral Development

Vertical Development

| Development of Scope / Development of Detail | Single Thread | Replication | Synthesis |
|---|---|---|---|
| System | | | |
| Subsystem | | | |
| Function | | | |
| Task | | | |

Figure 2. Lateral and vertical development phases.

Development of detail. - The development of detail is a two-part affair which we shall call analysis and design. The distinction between these two parts is critical when one distinguishes between requirements and means. Any phase of the detail development process can be schematized as shown in Figure 3. In this scheme, analysis is that part of the process which is concerned with the determination of the consequent or next lower level of requirements and constraints for which subsequent, more detailed design solutions must be determined. The design part of the process is that part which is concerned with the efforts necessary to arrive at an acceptable, real solution to a given set of requirements and constraints. Another difference between analysis and design is that design has the option of more than one alternative, i.e., there may be several design solutions to any one set of requirements. Analysis, however, seldom has any options, i.e., for any one design solution, there is only one set of optimum consequent requirements. Thus, analysis serves the role of taking any design decision and determining the next lower level of requirements and constraints needed to support that design.

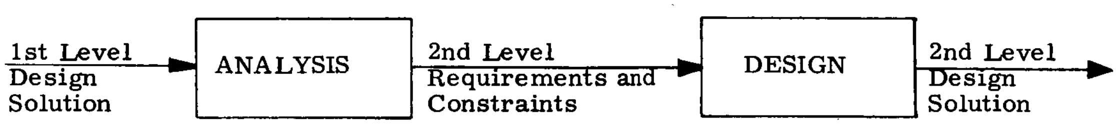



Figure 3. The detail development process.

As far as the development sequence is concerned, the development process is carried out at many different levels of detail down to the point where all design is completed and the system can be built (ignoring the development of scope). For purposes of discussion the system development sequence is a four level process, occurring as a sequence* of four analysis and design efforts. The fact that an actual system development effort may not fall into four sequences is unimportant. It is important that one

*The term sequence, as opposed to the term series, is used advisedly. A sequence may have repetition, i.e., 1, 2, 3; 1, 2, 4; 1, 2, 5; etc. A series does not allow repetition, i.e., 1, 2, 3, . . . . . , n.

recognizes that there are different degrees of analyses and design decisions and consequent data required to develop a complex system. These four levels of system development are depicted in Figure 4. The first level of system development, concerned with requirements analysis and advance design, is shown separated from the other three levels for two reasons. First, this level of system development is typically performed by the customer or ultimate user of the system (at least by implication) prior to the actual initiation of the other three levels of system development. Second, the last three levels of the development sequence represent the development efforts which are typically contracted. These are the kinds of effort usually thought of as system development. For purposes of this paper, the efforts above the dashed line of Figure 4 are referred to as "advance development" and those below the dashed line of Figure 4 as "system development".

Advance development includes requirements analysis and advance design. Requirements analysis is that activity concerned with analyzing policy of a national, organizational, or individual nature with respect to deriving the system development and operational criteria, or what might be called the political/strategic/tactical requirements and constraints. Advance design is that effort concerned with development of a system concept compatible with the level of system criteria developed during requirements analysis. This really means the design solution is compatible with the policy level. The efforts of requirements analysis and advance design obviously interact and are not two clear-cut efforts as shown on the diagram. The same thing is true, of course, for the three levels of system development, although it generally is the case that the further we progress through the development process the more clear-cut and separated analysis and design efforts become. This is because each successive level is more concrete than the previous and the requirement versus means distinction is easier to make.

Figure 4 depicts the analysis and design process in such a way as to emphasize the fact that these activities go on at four levels of abstraction.

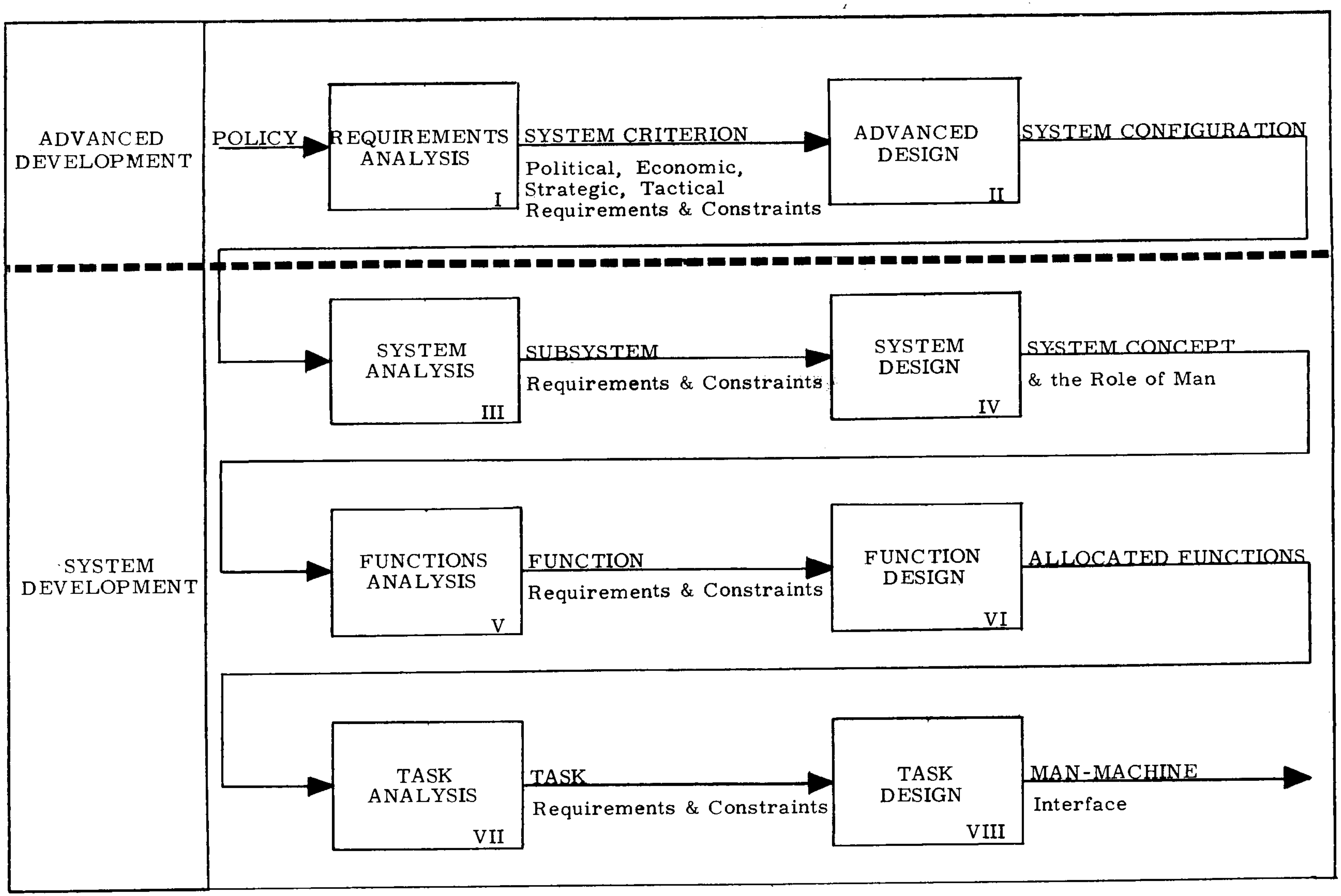



Figure 4. The major efforts of a logical man-machine system development sequence.

It is recognized that in actual practice there is considerable interaction between the four levels. That this should be the case is understandable. The analysis at the i + lst level constitutes a check on the adequacy of the design effort on the i th level. The check on the adequacy of the design effort at the fourth level is the operational effectiveness of the system. The consequence of this is that, in actual practice, work goes on at several levels of analysis and design. A difficulty arises in that work at the different levels becomes confused. Design decisions may be made at the i th level which should only be made at the i + x th level after adequate analyses have been performed. Thus the discussion of Figure 4 is intended to isolate the kinds of considerations which must be made at each level, so that adequate decisions may be made at the next lower level.

The three levels of system development proposed here have proven useful empirically. Other investigators elude to the concept of approximately three levels of system development. These three levels of system development are referred to here, respectively, as (1) system analysis and design, (2) functions analysis and design, and (3) task analysis and design. These three levels of system development are also oriented toward the development of human performance in systems rather than hardware performance. System analysis and design is concerned with the derivation of subsystem requirements and constraints and the development of the role of man in the system configuration. Functions analysis and design is concerned with the derivation of subsystem functions and the allocation of these functions to men and machines. Task analysis and design is concerned with the derivation of human performance tasks and the design of the man-machine interface for accomplishing these tasks.

Development of scope. - For many large scale man-machine systems development may also take place with respect to scope (lateral development). For example, the New York Stock Exchange consists of many replicated units throughout the United States. Each of these units takes actions and processes information locally, and transmits information to and receives information from a central unit. The FAA, as an information processing system, is another example. This process of developing many units will be called Development of Scope. Development of scope may be necessary at any level of development of detail from entire systems through subsystems, functions and tasks. The development of scope is considered to occur over a three step range, i.e., single thread, replication, and synthesis. Similar to the development of detail, it is not important for the development of scope that a particular system development effort may not fall into three different levels. It is important that one recognize that there are different degrees of complexity as design solution of different levels of detail are replicated and synthesized.

The first step in the development of scope is single thread development. This is essentially the simplest version of the real system which will operate on the basis of single inputs to produce criterion output with the required system reliability. The single thread design for a fleet of supersonic transports for example would be all of the personnel, equipment, facilities, and information it would take to operate and support a single vehicle (see Figure 5). The second step in the development of scope is the replication of the whole systems, subsystems, functions or task designs that would be required to meet the political, economic, stategic and tactical requirements of effort I, Requirements Analysis (see Figure 4). The supersonic transport fleet operation for example may require replication of the total system (vehicle and ground support) some subsystems (communications for example) and some functions and task level designs. The third step in the development of scope is the synthesis of the replicated designs into a complete system operation. It is more than likely that the replication of designs at any level may generate requirements for coordination and control which did not exist previously. To continue with the supersonic transport fleet example, the replications of airborne and ground equipment, facilities, personnel and information for the operation of many aircraft to many terminals obviously requires a great deal of scheduling, dispatch coordination, en route control, and terminal area coordination and control in order to synthesize the replications into an effective complete system. Most of the synthesizing performances are obviously FAA activities in this simplified example.

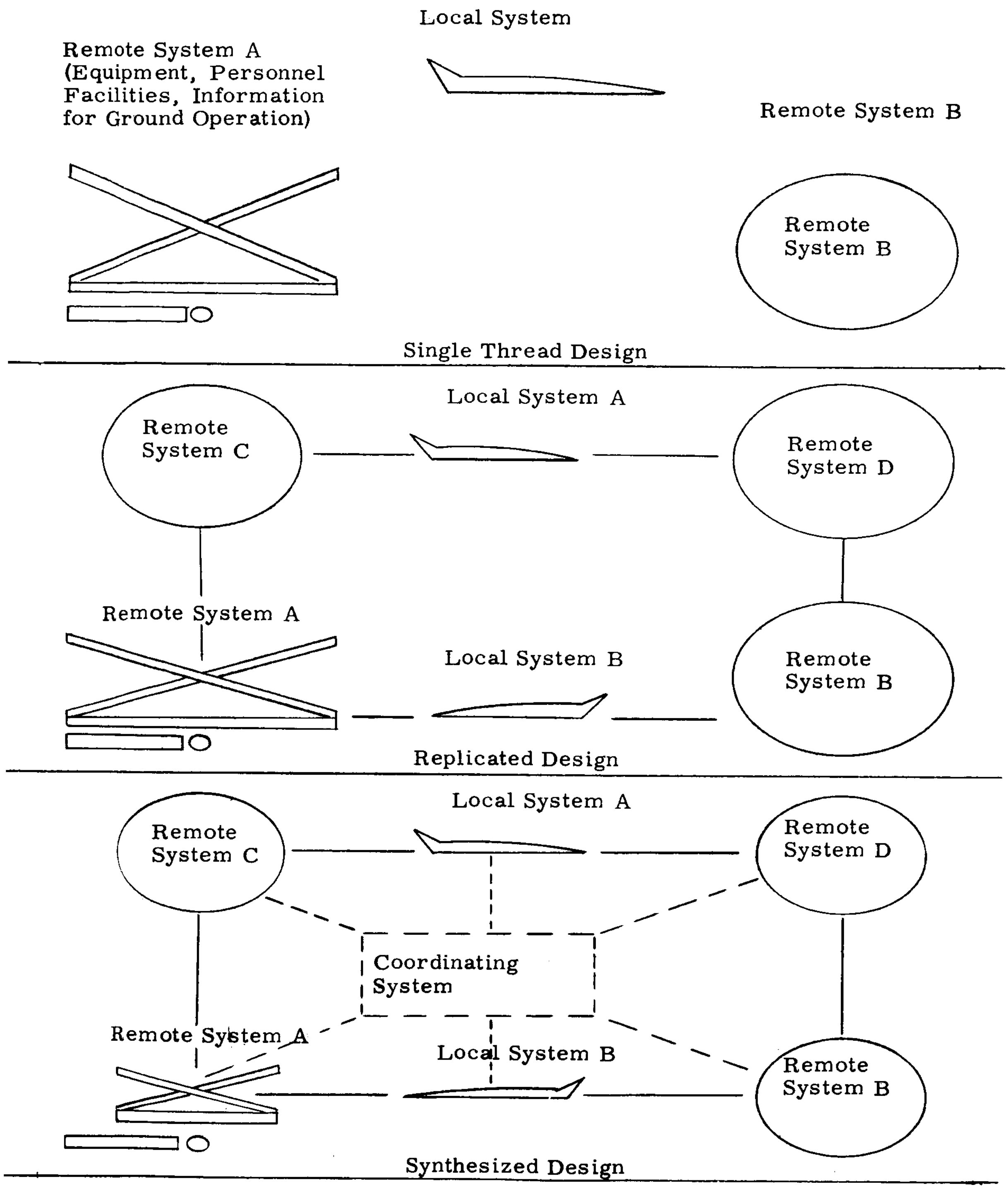



Figure 5. A simplified illustration of development of scope at the system level of detail for a supersonic transport fleet.

To reiterate, the system development process must encompass both the development of detail and of scope. The detail development efforts are referred to as subsystem, function, and task levels and the scope development efforts are referred to as single thread, replication, and synthesis steps. Most exploratory or experimental systems are developed in detail and there is little necessity for the development of scope.

Types of performance units. - The derivation of performance requirements and constraints is accomplished by both rational and quantitative analysis methods. While there are virtually no ways to guarantee inclusiveness for any type of rational analysis there are some systematic concepts which can be used.

In order to maximize inclusiveness of the analysis of given design decisions, for the purpose of determining and describing consequent performance units, it is helpful to distinguish three principal types of performance: multiplicative, additive, and monitoring performance units.

The classification of performance types is based on an assumption of two serial requirements in system development. The first is the specification of the tolerance limits within which the required system output must fall. The second is to maximize the reliability with which that output is obtained, within the given tolerance limits.

1. Multiplicative units are required to obtain system output performance within stated tolerance limits. Reliability is an additional, different consideration. Thus, in an extant system, one can identify multiplicative units by considering each unit in the system in turn and asking whether or not system output would be impossible to obtain if the unit were deleted from the system. For most complex man-machine systems, it will turn out to be possible to delete many of the units in the system without making it impossible to obtain the system output. Those units which survive as necessary for obtaining the output of the system will be called multiplicative.

If the output of any one of them were to go out-of-tolerance (i.e., to zero),*
the output of the total system must necessarily go to zero. The system which is defined in terms of multiplicative units is capable of output performance in the operational situation, although its reliability may be extremely low.

Having accounted for the required system output, within given tolerance limits, the next consideration is reliability.

2. Additive units are used to maintain output at the required level of reliability. Ordinarily, reliability of operational performance of complex man-machine systems is obtained by two general methods. The first of these is by the use of inherently reliable components within the multiplicative or prime system. The second is by employing additive units which can add performance capability back into the system whenever the performance of multiplicative units goes out-of-tolerance. For example, emergency power supplies are additive units. Additive units may also add other features, not necessarily directly related to performance, such as safety, confidence information, and filtering. In general it may be said of additive units that if the output of any of these units does not occur then the final system output may still occur.

3. Monitoring units are required as adjuncts to additive units. They function to sense a failure of a multiplicative unit in the prime system and "turn on" the additive unit. They are also used to sense any input and select among alternative outputs, i.e., a decision function.

Figure 6 presents a schematic diagram of a system containing multiplicative units X and Y, an additive unit, A, and a monitoring unit, M. In this figure the monitoring unit is shown with an "either/or" output indicating that the output from X being monitored by M goes either directly to Y or initiates the additive unit A which provides the necessary input to Y. Y can be initiated by the output of either M or A.

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*An output which is within tolerance limits is given a value of one; an output which is outside of tolerance limits in any way is assigned a value of zero.

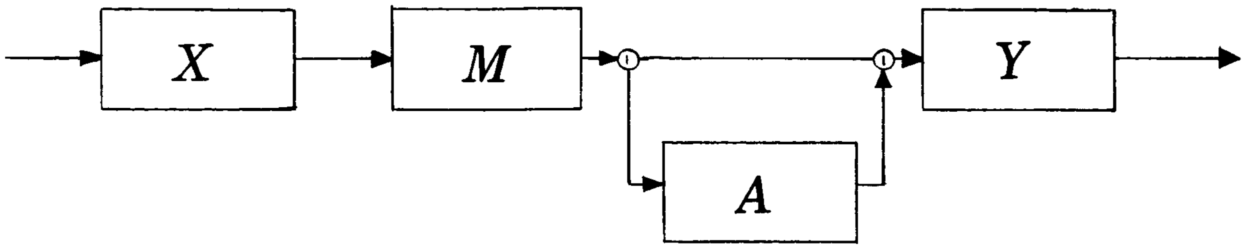


Figure 6. Schematic diagram of multiplicative, monitoring and additive units.

When performance units in a system are described as multiplicative, additive, or monitoring, it can be seen that maintenance subsystems are additive with respect to prime or operational systems. Thus, maintenance subsystems add back into the system the performance capability lost by the failure or deterioration of a multiplicative unit, just as redundant subsystems do. If maintenance subsystems are additive, two other things can be said about them: first, maintenance subsystems require monitoring units, and second, maintenance subsystems have to do with system reliability rather than directly with system performance output capability.

The concept described above can be used to analyze an extant system in order to describe its functions. It may also be used to analyze a given design solution, and to derive the consequent requirements of that solution. The remainder of the discussion of this concept will illustrate how these three types of performance units are successively derived to represent the requirements of a system design. The process of successively deriving the different types of performance units is illustrated in Figure 7 and explained below.

1. Multiplicative subsystems were distinguished as those units of performance which are so critical that system output drops to zero, or approaches zero, if the output of any multiplicative unit does not occur. Thus, the first subsystems derived during system analysis are these critical subsystems. The multiplicative subsystems of Figure 7 are shown simply as five subsystems in series, M-1 through M-5.

2. Additive subsystems are those units of performance which add to the probability that the final system output will occur. If the output of an

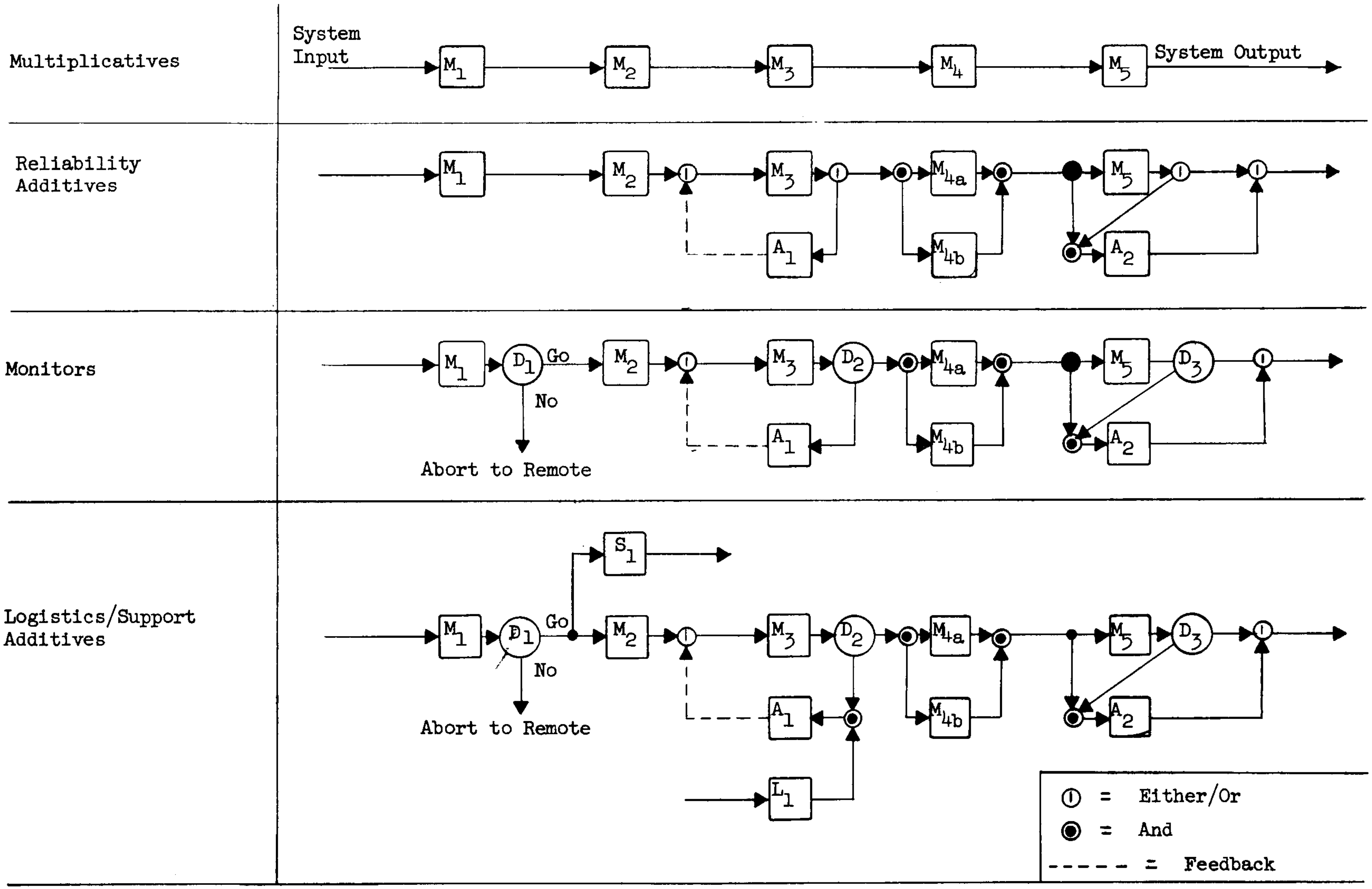


Figure 7. Types of subsystem performance and the successive derivation of the different types of subsystems.

additive subsystem does not occur then the final system output may or may not be affected. There are different kinds of additive performance but for the present all additives will be classified as one of two types: these are additives for reliability and additives for logistics/support.

a. Additives for reliability are those subsystems added to the multiplicative functions to provide back-up or maintenance to increase total system reliability. These subsystems are incorporated whenever the inherent output reliability of any multiplicative function is suspect or insufficient. This is one of the reasons why the system analysis and design efforts are actually carried out concomitantly. It is impossible to determine if additive subsystems are necessary until design decisions have been made with respect to multiplicative subsystems. In other words, we cannot question the output reliability of any multiplicative subsystem until we have decided on the means for obtaining that output. Figure 7 shows three different types of additives for reliability which can be considered:

(1) A-1 is essentially a maintenance type subsystem to bring the output of M-3 back into tolerance once it has gone out of tolerance. Utilization of this type of subsystem implies that there is a delay in time since no input is available to M-4 until the maintenance effort of A-1 has been completed and returned M-3 to operating conditions.

(2) Another technique for providing system reliability is to provide parallel or redundant performance units. This is illustrated in subsystem M-4 which is, in fact, two subsystems M-4a and M-4b. Each of these two new subsystems is individually an additive subsystem. However, together they represent a serial subsystem.

(3) A-2 represents a back-up system, wherein if the output from M-5 is out of tolerance the input from M-4 may be rerouted through A-2 to provide a satisfactory system output.

b. Additive logistic/support subsystems are those included for the purpose of providing the capability of supporting both multiplicative and additive subsystems. These subsystems are typically supply, storage or transportation subsystems. In Figure 7 a logistics subsystem is depicted as L-1 which would be the provisioning subsystem for the additive reliability subsystem A-1 (maintenance type subsystem). An independent support subsystem is depicted as S-1. In addition, there may be other additive support subsystems, not directly related to the system criterion output, but required to support some other aspect of the system, or to support some subsystem of an entirely different system.

3. Monitor subsystems are those units of performance included for the purpose of detecting when an additive reliability subsystem must be initiated. Thus whenever there is an additive reliability subsystem (except for parallel or redundant subsystems) a monitor subsystem must be included to detect when the primary subsystem output is out of tolerance, and then switch in the additive subsystem. In Figure 7, D-2 and D-3 are monitor subsystems to monitor the output of M-3 and M-5, respectively, and to switch in A-1 and A-2, respectively, as required.

Figure 7 illustrates how the different types of subsystems may be successively derived and connected to develop the total subsystem concept. All of the subsystems derived in this manner can be described in performance terms without regard to the means for implementing the performance of each subsystem. However, as indicated earlier the system analysis and system design efforts are usually carried out concomitantly. For example, subsystems are derived first, as part of system analysis; then system design is initiated to determine the role of men and machines in implementing each multiplicative subsystem; reliability allocation studies are performed to maximize the reliability of serial subsystems, additive subsystems are derived and man-machine system design carried out for each additive system, and so forth until all subsystems are derived and system design accomplished for each subsystem.

Man-machine capabilities and limitations. - Many approaches have been developed for analyzing man's capabilities and limitations with respect to system performance. Some approaches suggest that man and machines should be compared, for system performance, while others suggest that men and machines are not comparable but are complimentary. Some suggest that man should be designed into the system where possible, others suggest man should be designed out of the system where possible. There are numerous controversial issues concerning man's capabilities and limitations for system performance. The philosophy adopted here is (1) that man has certain unique capabilities and limitations which cannot be compared against machines, (2) there are many types of performance in which man can participate or which can be automated, and (3) for those performances where man does participate there is an optimum design to complement his capabilities and limitations. In general it may be stated that the concept proposed here is to develop a design solution for trade-off which exploits man's capabilities and compensates for his limitations. Four questions must be considered:

1. What are the limitations that constrain man's use in the system? This question must consider both system and individual factors, such as the following:

   a. Man comes in only one physical model and can only be integrated into the system concept as a physical whole, with certain general characteristics of size, weight, shape, strength, etc.

   b. Man has certain performance limitations such as sensitivity, reaction time, number of information channels, rate of operation, environmental stress tolerance, etc.

   c. There is a definite price to pay for maintaining reliable performance potential in man, in terms of training, maintenance of proficiency, manuals, handbooks, instructions and other job guides.

   d. Man has physiological needs. His performance deteriorates rapidly when these physiological needs, such as nourishment, environmental protection, sleep, comfort, and general health are not satisfied.

e. Man has psychological needs. His performance usually deteriorates over prolonged periods of high stress or nonactivity, and can change significantly as a result of such psychological variables as motivation, frustration, conflict, fear, etc.

2. What systems performance requires man? It is assumed that there are some types of performance which must be implemented by man, at least within the present state-of-the-art. In a report titled An Approach to Functions Analysis and Allocation, Shapero, Rappaport and Erickson (85) develop a criterion for deciding when man is required in the system. They assert:

> "In any system (or function) of human design, man is necessary wherever the assumptions concerning the relationships between inputs and outputs are subject to re-examination and restructuring in the operational context."

This criterion is restated "in a more limited form for use in analyzing functions . . . . (page 21 as follows: In any system (or function) of human design, man is necessary wherever the form, and/or content of all of the inputs and outputs cannot be specified."

We do not necessarily believe that this is the sole criterion, or that there is in fact a simple single criterion, but criteria can be developed to determine when man is required for system performance. For example, the lesson of the Mercury program can be stated as a criterion for human participation. In any system (or function) of human design, man is necessary wherever an automated performance possesses a high likelihood of failure or malfunction during the period of mission accomplishment.

3. What system performance could be implemented by man? This question is concerned with those kinds of system performance which can be done either (1) manually or by man with machine aids (mechanized) or (2) by machine alone (automatically). There are a wide range of system performances at all levels (subsystem, function and task) which can be performed by man

or by machine. For example, consider the requirement for monitoring the electrical output of a piece of equipment. This monitoring may be accomplished automatically with comparator circuits or by man viewing the output on a display (mechanized). The optimum manned design should be developed and the choice between this and other designs (manned or automatic) must be based on trade-off's considering system effectiveness, reliability, cost, etc.

4. Given man's required (question 2) or feasible (question 3) inclusion in the system, what can be done to use his unique capabilities to maximize his performance reliability in the system? This question is concerned with "human engineering" in its grammatically correct sense, i.e., we can "engineer the human" to affect his performance. True—we cannot lengthen his arms, increase his range of auditory perception, or make him do things he is not intrinsically capable of, but we may "engineer" his attitude. This can be accomplished by actually changing his attitude through psychological techniques or designing acceptance features into the system during development. Man has other unique human capabilities, such as his ability to learn and to adapt, which must also be considered with respect to increasing system effectiveness.

Optimal manned design solutions. - The previous concept established that man and machine could be compared or traded off for some types of system performance and not for others, and there were some critical questions concerning man's performance capabilities and limitations to be considered. The philosophy adopted here is that there is an optimal manned design solution for any system requirement, although the optimal manned design solution may not be the best over-all system solution. System developers should develop an optimal manned design solution which can be evaluated against automatic design solutions. Further, an optimal manned design solution is one in which man has the most responsible/authoritative/acceptable (R/A/A) role which he can perform while also being protected and sustained. It is proposed that the concept for approaching consideration of man's capabilities and limitations should be to design man into the system with the most responsibility, authority, and acceptance feasible within the system requirements and constraints. This concept is based on the following rationale.

1. Historically the attempt has always been to extend man's capability and usefulness rather than to eliminate man. Developments in the physical sciences have been consistently oriented toward providing man with a better understanding and a better capability to participate in his current environment.

2. Acceptance by human operators within the system will be greater toward the higher responsibility/authority (R/A) roles than toward the lower R/A roles. It is now known that acceptance is definitely negative if human beings are designed into the system at a lesser level of R/A than they are capable of accepting and performing. The result is to reduce system reliability.

3. The higher R/A roles in systems are apt to have more cognitive performance associated with them. These types of performance are where man does excel and where it is difficult and expensive to build equivalent machines.

4. Design decisions concerning the implementation by men or machines for the higher order of R/A roles will influence the requirements for the lesser order of R/A roles. Thus every conceivable means, including utilization of man, must be considered to approach the optimum design solution and reduce the negative consequences of poor design.

5. It is well documented that man is a major component providing consistency in system performance. Since consistence of performance contributes to system performance reliability, man may be viewed as a major contributor to system performance reliability. This concept is based on the assumption that there are different levels of responsibility and authority associated with different types of performance. It also appears (based on the work on this project to date) that the importance attached to any role is dependent on the level of responsibility/authority, and that this is correlated with the degree of acceptance by man of his role in the system. That is, the greater the role man has, the more acceptable that role is to him. In summary, therefore, the optimal role of man is defined as that role which has the most responsible/authoritative/acceptable features feasible.

6. When man is included locally in a system, one of the usual reasons is to have him available to deal with unusual and unforeseen events. It is man's recognized aptitude for reprogramming or redesigning his role on the spot to deal with the unexpected that is so valuable, because it will increase system reliability. However, this is an aptitude of man, not a subsystem output achieved at no cost to the system or system designers. Like all required outputs it is not free but requires inputs. In order to be able to effectively redesign his role, in unusual or emergency situations, two preconditions must exist, and at this point in the design we must determine if in fact they will exist. These preconditions are as follows:

a. The man must understand the over-all function of the system, and more specifically the subsystem he is interfacing with, his role in it, and how all automatic functions operate for which he might have to provide total or partial back up. Where man is not given adequate explanations as to how functions other than his own are performed, particularly machine functions, he will make up his own explanations, as has been pointed out by Firstman and Jordan (30). These explanations will more than likely be incorrect and, therefore, not an effective tool in an unforeseen situation.

b. Man must be proficient at rapidly solving new and unforeseen problems in the subsystem environment. It has been demonstrated that this capability can be learned. Such capability has been labeled <u>learning how to learn</u>, or more simply as a <u>learning set</u>. However, this ability can be created and maintained only by giving the man the responsibility and freedom to continually try out new tasks and methods. Obviously it is not possible to produce the capability in man to deal with unforeseen events by selection, traditional training methods, or job guides.

Therefore, if man is to be placed in a system, particularly locally, in order to increase system reliability by having him as an additive for dealing with unforeseen events, it is essential to give him as much responsibility and authority as is feasible. Maximum responsibility and authority are necessary to permit him to develop a learning set so that he will have the capability to deal with unexpected events.

There are at least three variables which affect the optimal role man has in a system. The first variable is the type of performance unit man participates in and is simply whether man plays a multiplicative or an additive role with respect to system outputs. If man participates in any of the multiplicative subsystems he has a multiplicative role. If he participates in any of the additive subsystems man has an additive role. It is further believed that additive subsystems have a relative order of responsibility, i.e., reliability subsystems have the most responsibility, monitor subsystems the next order of responsibility and logistical support subsystems the least order of responsibility.

The second variable is location of performance. For present purposes, location has been limited to either local or remote. Local refers to the mission environment in which the system operates. Remote refers to some location away from the immediate mission environment where man may be protected and sustained. With respect to the location variable, it is suggested that local performance carries more R/A value than remote performance.

The third variable we have termed human participation. This is a continuum from completely manual to completely automatic implementation of a subsystem requirement. We utilize two categories of human participation, namely, manual or mechanized. Manual refers to the situation where all of the performance required in any subsystem implementation is performed by a human being. Mechanized refers to the situation where the performance required for implementation of a subsystem is accomplished by man together with mechanized extensions of man's capability. The variables of types of performance units (multiplicative and additive) and location of performance (local or remote) have been discussed elsewhere. The third variable mentioned above, i.e., extent of human participation (from manual to mechanization) has not been introduced before and may be clarified by the following example, in Figure 8.

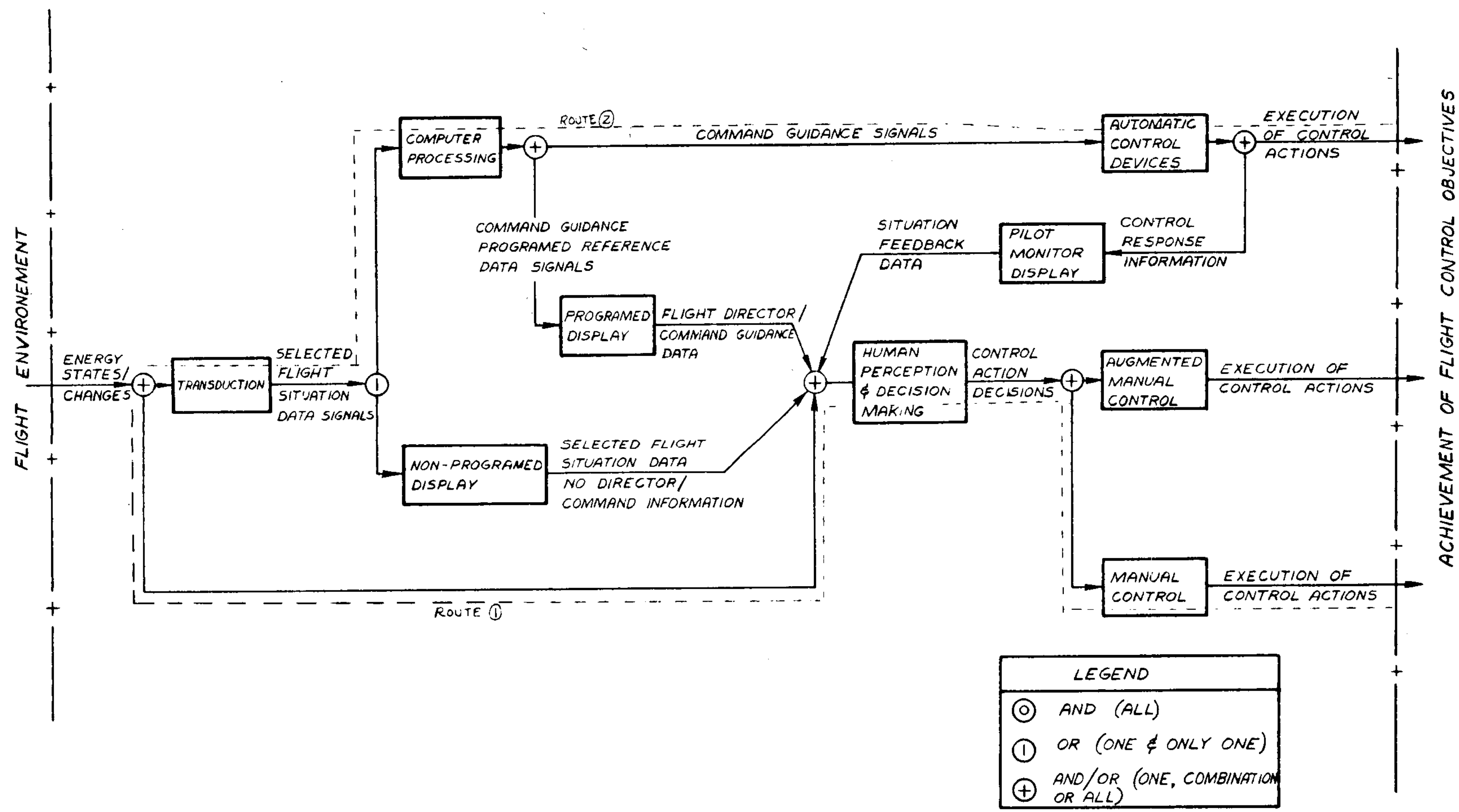


FIGURE 8. DIFFERENT POSSIBLE COMBINATIONS OF PERFORMANCE UNITS TO OBTAIN FLIGHT CONTROL OBJECTIVES.

This figure of a local multiplicative subsystem shows several different kinds of performance events which, in combination, provide different routes for accomplishing the same objective, viz., flight control. The routes differ in the level of human participation. Route 1 is the most manual route. Route 2 is a completely automatic route. There are several other route possibilities in-between 1 and 2 which represent various "mechanized" routes wherein human participation is augmented by some means or other.

The concept of developing the optimal manned design solutions, i.e., solutions in which man has the most responsible, authoritative, acceptable role feasible, is a key concept to this program.

## III. SEQUENCE AND ACTIVITY DESCRIPTIONS FOR THE SYSTEM DESIGN EFFORT

The purpose of this section is to apply the concepts outlined in section II to develop a method for determining the role of man in a system. While it is realized that, in practice, this is not done in isolation from the design and development of equipments, it is felt that it is not necessary to consider equipments in the discussion of the method. The attempt is not, in fact, to design a system. Further, until the role of man is determined, the role that equipments will play cannot adequately be determined.

The intention is to develop a descriptive model which could be used to determine the role of man for any system. Role is the summation of all man's subsystem performance regardless of mission, size, complexity or operational environment. This makes it necessary to consider a number of factors which are not usually considered in system design, especially of terrestrial systems. A specific example is the emphasis on the ecological constraints and the effects of acceleration, vibration, etc. While these factors have always been important, there will be more emphasis on them as man begins to develop systems for space travel and exploration of the moon and the other planets.

The discussion of this section will be centered around Figures 4, 9 and 10. Figure 4, which is discussed in section II, is a schematic of the major effects of a logical man-machine system development process. It outlines the essential efforts which must be done, but does not consider the sequencing of these efforts. Figure 9 focuses on one effort of the system development process, that of system design. It is here that the role of man must be determined. Figure 10* expands the discussion of each of the sequences of activities mentioned in Figure 9.

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* Figure 10 will be found inside the back cover.

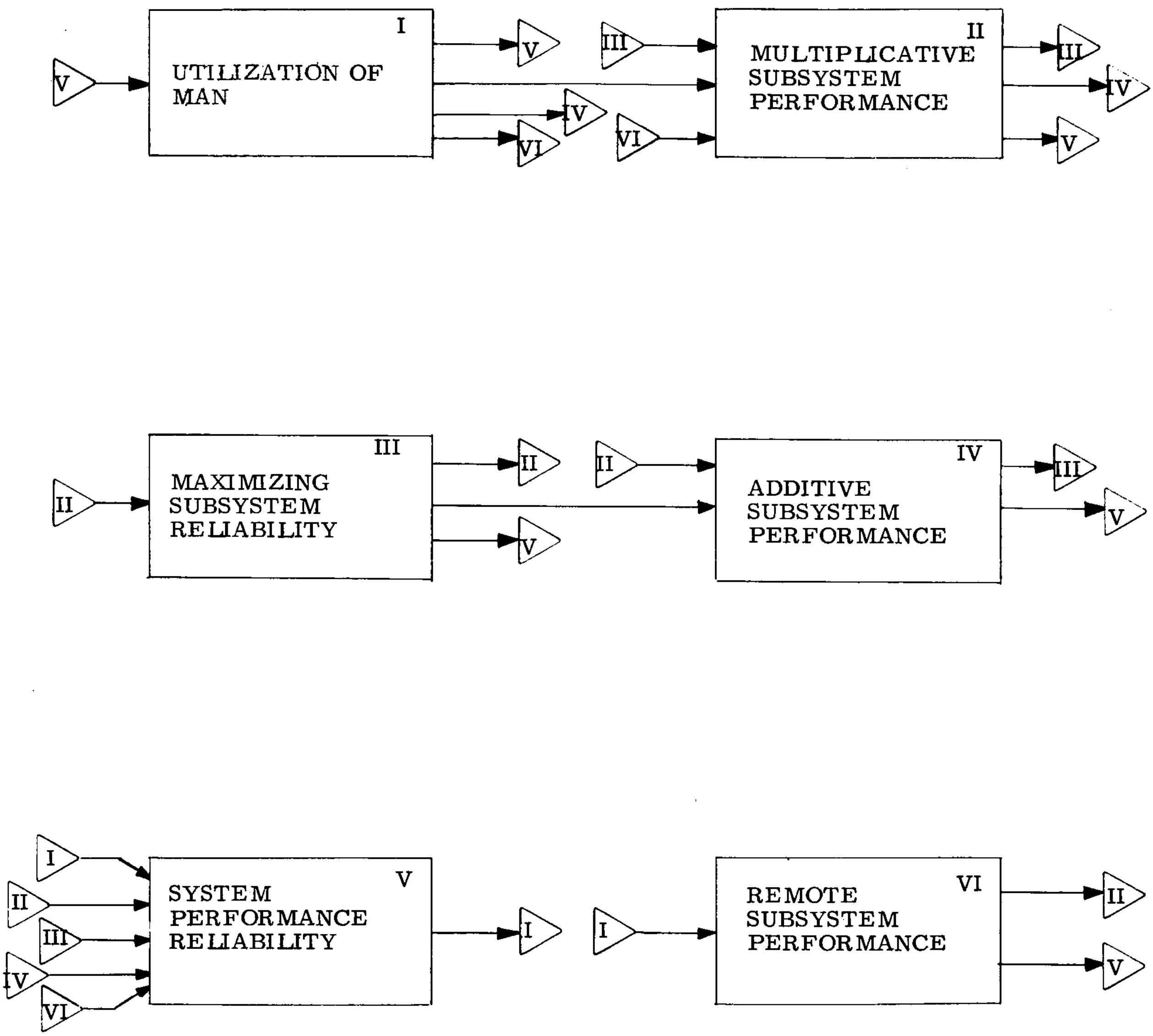


Figure 9. Sequencing of activities in the development of the role of man.

It is first necessary to note the system design effort, box IV of Figure 4. This effort includes the system design sequences to determine the role of man which are depicted in Figure 9. Figure 9 shows six sequences of activities which comprise system design and the inter-relations among them. The six sequences of activities are described as:

I. Utilization of man;
II. Multiplicative subsystem performance;
III. Maximizing subsystem reliability;
IV. Additive subsystem performance;
V. System performance reliability;
VI. Remote subsystem performance.

Sequence I, Utilization of man, is concerned with determining whether man can play a local role in the system. If it is found that he can, there are potential problems of the support requirements to maintain man in the system environment. Sequence I outputs to sequences II, IV, V and VI. In the case of multiple manning, sequence I receives an input from sequence V.

Sequence II, Multiplicative subsystem performance, is concerned with developing local manned multiplicative performance means, local performance support requirements and the specification of techniques to develop the required performance capability. Sequence II outputs to sequences III, IV and V. Sequence II receives inputs from sequences I, III and VI.

Sequence III, Maximize subsystem reliability, is concerned with determining whether subsystem reliability requirements are met by the manned solution, what may be done to enhance subsystem reliability, if necessary, and the consequences of enhancing subsystem reliability. Sequence III outputs to sequences II, IV and V. Sequence III receives an input from sequence II.

Sequence IV is the counterpart of sequence II for local additive performance. Sequence IV outputs to sequences III and V and receives inputs from sequences II and III.

Sequence V is concerned with developing manning requirements, synthesis of support requirements, the manned system concept and estimating system performance reliability, all for local system performance. Sequence V receives inputs from all other sequences and outputs to sequence I.

Sequence VI is the counterpart of sequence I for remote system performance. Sequence VI outputs to sequences II and V. It receives an input from sequence I.

We may now proceed to elaborate each of the six sequences of activities. Refer to Figure 10.

### Sequence I. Utilization of Man.

The purpose of sequence I is to determine whether man can be utilized locally in the system. If it is found that he can be so utilized, the next question is whether he is necessary to the accomplishment of the system missions. Finally, if man is not required for system mission accomplishment, it may still be desirable to include him as a system component.

Sequence I should be completed before any of the others, if possible, for reasons of efficiency and economy in system development. If it should be found that man cannot be utilized locally and that he must be used in a remote role, there is no reason to develop any manual or mechanized design solutions for the local subsystems. In this case manual and mechanized performance means design can be carried out for remote subsystems. On the other hand, even if it should be determined a priori, as a policy decision, that man will participate locally, sequence I should be accomplished first since appropriate ways in which man can be utilized will be determined.

Sequence I contains nine activities:

1. Determination of human anthropometric requirements and constraints;
2. Analysis of local system/anthropometric physical compatibility;
3. Determination of human ecological requirements and constraints;
4. Analysis of local system/ecological requirements and constraints;
5. Analysis of techniques for compensating for local stress;
6. Determination of criteria for required human performance and limitation of human performance;
7. Determination of whether man is mandatory for local system performance;
8. Determination of support requirements for local stress compensation;
9. Determination of whether man is feasible for local system performance.

The nine activities of sequence I fall into four different groupings. Three of these groupings are alternative starting places:

1. Anthropometric requirements and constraints, activities 1 and 2.
2. Ecological requirements and constraints, activities 3 through 5 and 8.
3. Human performance capabilities and limitations, activity 6.

The fourth grouping, which is dependent upon the completion of the other three, determines the nature of man's local role in the system, activities 7 and 9.

Activity 1. Delineation of human anthropometric requirements and constraints. The philosophy which led to the present ordering of sequence I tasks was that those activities which would eliminate man the quickest should be considered first.

Activity 1 requires inputs of known anthropometric data tabulations. A typical and good source is (66). The output of this activity is information about body measures. These are input to activity 2 for comparison with relevant information from the multiplicative subsystem requirements and constraints. The output of activity 1 goes also to activity 30.

Activity 2. Analysis of local system/anthropometric physical compatibility. The purpose of this activity is to determine whether anthropometric considerations will preclude man from assuming a local role in the system. Inputs to this activity are the anthropometric data generated in activity 1 and relevant information from the multiplicative subsystem requirements and constraints, such as volume and weight constraints.

The procedures used involve a comparison of available space and payload capability, as determined by subsystem requirements and constraints, with the requirements for human task performance, as for example:

| Anthropometry | Subsystem R & C |
|---|---|
| 95th Percentile body volume | Available space |
| 95th Percentile body weight | Space distribution |
| Task performance postures | Force requirements |
| Body movement range/posture | Payload capability |

The output of activity 2, inputs to activity 7, if man is not precluded from assuming a local role. If man cannot perform a local role due to anthropometric considerations then he can, at best, contribute remotely, sequence VI.

Activity 3. Delineation of human ecological requirements and constraints. This activity is an alternative starting point to activity 1. Like all animals, man is restricted as to the range of environmental conditions which he can tolerate. On the one hand, there is an optimal set of environmental conditions for human habitation. On the other hand, the range of many of these conditions is quite broad in man's case. The purpose of activity 3 is to assemble pertinent data about the scope and range of environmental conditions which would restrict the utilization of man in a local system role. The inputs to this activity come from both the biological and the social sciences (14, 25, 66, 76).

The output of this activity is a listing of the various environmental factors which restrict man's usage, e.g.*

Climactic requirements
Atmospheric hazards
Vibration tolerance
Work, recreation and rest
Nourishment and sustenance
Waste and sanitation
Acceleration
Medical problems
Human stability
Accident potential

This output of activity 3 inputs to activities 4 and 27, both of which have to do with determining specific ecological constraints on the system, if man is used.

Activity 4. Analysis of local system/ecological requirements capability. The purpose of activity 4 is to compare the output of activity 3 with the appropriate requirements and constraints as developed in the system configuration, to determine when the two sets of requirements will be incompatible and the degree of incompatibility. Information from the system configuration falls into the following categories:

1. The operational concept
2. The support concept
3. Local and remote system boundaries
4. The operating environment
5. Estimated performance reliability
6. Developmental constraints

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*The appendix constitutes a more detailed listing of these factors.

7. Cultural constraints
8. Personnel constraints
9. Equipment constraints
10. Available space
11. Space distribution
12. Force requirements
13. Payload capability.

The procedures here are to compare systematically the human ecological requirements and constraints with the system requirements and constraints. For example, if the equipment and/or payload constraints preclude the use of air conditioning equipment for a space vehicle, it is unlikely that man would be able to survive, let alone work, in the space environment. On the other hand, if the support concept for an orbital space laboratory calls for re-supply every two weeks, some vehicle space which might have gone to storage of supplies may be released for other purposes, e.g. an exercise room for laboratory personnel.

The output of activity 4 is input to activities 7 and 5. If no incompatibilities between the ecological and system requirements and constraints are found, one may proceed directly to activity 7. If incompatibilities are found then the input is to activity 5.

Activity 5. Analysis of techniques for compensating for local stress. The intent of this activity is to find ways to compensate for incompatibilities between human ecological requirements and the system requirements and constraints. Examples of such techniques are the g-suits worn by pilots of high performance military aircraft and the artificial atmosphere of the Mercury capsule. Specific instances of the need for such techniques are generated in activity 4, which constitutes one of the inputs to activity 5.

The procedure of activity 5 is to match specific ecological requirements with appropriate ways of compensating for the violation of that requirement in the system requirements and constraints.

The output of activity 5 goes directly to activities 7 and 8 when it is possible to compensate for human ecological requirements. If it is not possible to compensate for human ecological requirements, then man must play a remote role, (sequence VI).

Activity 6. Delineation of criteria for required human performance and limitation of human performance. Activity 6 is a third alternative starting point for sequence I. The purpose of this activity is to establish human performance criteria which can be used to determine whether man is required in the subsystem, activity 7, and to establish human performance limitations to determine how man's performance will effect the subsystem, activities 7 and 9.

The input to this activity is human performance data. There are two sets of such data which are pertinent.* The first concerns performance where the human is required:

1. The reliability of human task performance;
2. The reliability which man can provide to subsystem performance, by serving as a monitor;
3. The management and coordination role which must be played in the subsystem;
4. The non-system oriented behavior which is required, e.g., scientific observations.

The second set of data is concerned primarily with man's limitations which may affect these performances:

1. Psychophysiological reaction to stress;
2. Personality variables;

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*The appendix considers these in more detail.

3. Data sensing, processing and transmission capabilities and limitations;
4. Decision making capabilities and limitations.

Many of these data items are available, particularly when the behavior in question is pertinent to large scale military data processing systems. However, to the knowledge of the writers there is no convenient compilation of these items. A number of more or less complete summaries are available ( 32, 76, 94, 104). However, these have the disadvantage that they are usually in the form of comparative statements, e.g.

| Man | Machine |
|---|---|
| Man has relatively limited channel capacity. | Machines can have unlimited channel capacity. |

Such a statement might be quite valuable if one were designing an information processing system where space was no problem. But for, say a space-vehicle, where space is strictly limited one wants to know:

1. How many channels for reception can man exercise reliably?
2. How much will it cost to prepare men to function adequately in the anticipated situation?
3. What will it cost to build a machine to function in the anticipated situation, with a given reliability?
4. What space, weight, power and maintenance demands will be placed on the system by the machine?

It is quite likely that question 2 would have to be answered by recourse to experimentation.

The output of this activity feeds directly to activities 7 and 9. In addition, the output of activity 6 will be used in sequences II and IV.

Activity 7. Determine if man is mandatory for local system performance. The intent of this activity is to determine whether man must be in the system. The inputs to this activity come from the statement of the system configuration, system requirements and constraints and activities 2, 5 and 6.

In general man is mandatory to:*

1. Achieve a satisfactory system reliability;
2. Perform management and control tasks which require judgment as opposed to decision making;
3. Perform non-system oriented tasks;
4. Increase the diversity of missions which the system is capable of achieving.

The output of this activity goes directly to activity 10, sequence II, if man is mandatory. If man is not mandatory, then the output of activity 7 is to activity 9. It is recognized that frequently a decision to include or exclude man is made during the development of the system configuration. If the decision is to include man, then the approach to sequence I should probably be via activity 6, to develop the most useful and meaningful roles for man. This initial approach through activity 6 should be supplemented by chains initiated by activities 1 and 3, to develop an environment which will allow man to function optimally.

Activity 8. Delineation of support requirements for local stress compensation. The purpose of this activity is to determine how man will have to be supported to enable him to live and function adequately in the given system. These determinations begin with the input from activity 5. A second input is from activity 24, sequence V. The input from activity 24 occurs after manning requirements have been determined. The output of this activity is a delineation of the following factors required for support:

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*The appendix considers these in more detail.

1. Equipment
2. Personnel
3. Facilities or structure
4. Material

The output from activity 8 goes to activity 9, to help in the decision as to whether it is feasible to have man in the system. In addition, the output from 8 goes to activity 25, sequence V, where all support requirements are synthesized.

Activity 9. Determine if man is feasible for local system performance. The purpose of this activity is to determine whether there are system performance requirements which would utilize man's skills and capabilities, and at the same time assist in meeting developmental, equipment, operational or cost constraints. It is conceivable that even though man is not mandatory for a given system, there might be many reasons for having him there. Examples of such reasons include:

1. The expense involved in building and maintaining machines to perform tasks which man can perform with relative ease, e.g., pattern recognition;
2. Man is low cost and has low maintenance requirements for available complexity;
3. Man has relatively small weight, space and power requirements;
4. Man has high tolerance for ambiguity and noise in the task input;
5. Man has the potential for using alternative routes to achieve a given mission;
6. Man is quite reliable in relation to cost and complexity.

Additional instances of the use of man instead of a machine may be found in references 18, 34, 66, 84. For example, if a given subsystem performance should require a pattern recognition capability of some complexity, and the system were to be operational in three years, it would be desirable to use a human for that task. On the other hand, if enough money and time were available, it might be decided to push some of the research approaches to automatic pattern recognition (29, 38, 54, 56).

If it is determined that there are roles which it is desirable for man to perform, even though he is not required, the output of activity 9 goes to activity 10, sequence II. If there are no system roles which it is desirable for man to perform and he is not required, then man can only play a remote role in the system, sequence VI.

### Sequence II. Multiplicative Subsystem Design

The purpose of sequence II is to design the multiplicative subsystems which will be required in the finished system. As indicated in section II above, multiplicative subsystems are those which are required to achieve the system output. The activities which comprise sequence II are to be completed for each of the required subsystems. If a system is to contain five subsystems, then sequence II would be completed at least five times. It is likely that more than one alternative multiplicative performance means will be generated for each subsystem. If each of these meets all of the system requirements and constraints, a choice can be made among them in terms of:

1. The role of man as derived in sequence I;
2. Subsystem reliability requirement, sequence III.

Sequence II follows after sequence I since it is necessary to determine the multiplicative subsystems and their reliability limitations before one can determine requirements for additive subsystems.

Sequence II contains four activities:

10. Design of alternative feasible manual multiplicative performance means;

11. Design of alternative feasible mechanized multiplicative performance means;
12. Allocate human performance development means;
13. Determine multiplicative performance support means.

The four activities of sequence II may be thought of as forming a branched path. Activities 10 and 11 form a linear series. Activities 12 and 13 may be conducted at the same time, even though they are not independent of each other.

Activity 10. Design of alternate feasible manual multiplicative performance means. Manual task performance implies that a man performs the task; generates or accomplishes whatever power, energy or energy transduction is required; and controls the application of power or directs the utilization of the given energy. No assumptions are made about the nature of the task. It may involve the utilization of human receptors or effectors, or both. The definition does not preclude the use of tools, e.g., a plane, a lever or a telescope. The tool merely extends mans raw capabilities. The purpose of this activity is to develop manual performance means for each of the subsystems, insofar as this is possible. At this level of the design process the details of performance by which these various means are utilized will be as yet unknown. However, enough detail must be available so that the factors which will effect the use of that means can be specified. Enough detail about performance means must be available so that experiments could be designed to assess the reliability of that performance means. For example, consider the task of taking readings on the relative position of a spacecraft with respect to several of the heavenly bodies, to determine the position of the spacecraft. Of the various means which might be available, which could man use most consistently to achieve a prescribed accuracy? The errors in the readings will be a function of, at least:

1. The type of instrument;
2. Distance of spacecraft from the reference body;
3. Time required to make the measures;

4. Sequence of making measures on the several bodies;
5. Error inherent in a given instrument.

Such information would allow the design of a study to determine whether man could perform such a task adequately within the requirements of the subsystem mission.

The inputs to activity 10 are:

1. Results of activity 7 or 9, or of activity 18, sequence III;
2. Human performance data;
3. Multiplicative subsystem requirements and constraints, from system analysis;
4. Multiplicative subsystem reliability requirements, from system analysis.

The process of accomplishing activity 10 is essentially to determine the most responsible/authoritative/acceptable role commensurate with man's ability to perform the necessary tasks within the system requirements and constraints, and to estimate the reliability - consistency - with which he can so perform. Two sets of data are required. First, data on the range of performance values and the accuracy with which man can perform the given kinds of tasks - for comparison with requirements and constraints information. Second, data on the reliability of human task performance. Such data may be available sometimes, but for many of the tasks associated with one-shot systems these data will have to be generated during system development.

The output of activity 10 is to activities 12 and 13, if manual multiplicative subsystem performance means exist. If such means do not exist the output is to activity 11.

Activity 11. Design of alternate feasible mechanized multiplicative performance means. Mechanized task performance implies that a man performs the task; a machine generates or accomplishes whatever power, energy or energy transduction is required; a man controls the application or directs the utilization of the given energy. Again, no assumptions are made about the nature of the task. The tool does more than extend man's raw capabilities. Examples are the radio telescope, search radar, a bottling machine or a desk calculator. The purpose of this activity is to develop mechanized performance means for each of the subsystems for which manual means were not feasible, insofar as this is possible. Remarks concerning the amount of detail associated with these performance means, made in the discussion of activity 10, apply here also.

The inputs to activity 11 are the same as for activity 10, with the addition of data on equipment capability. Remarks about the process of accomplishing activity 10 apply here also.

The outputs of activity 11 go to activities 12 and 13, if mechanized multiplicative subsystem performance means exist. If such means do not exist and it is a matter of failing subsystem requirements and constraints, mechanized subsystem performance is not feasible. Subsystem performance will have to be accomplished automatically. In such an instance man can at best perform a remote role, sequence VI. If it is a matter of failing subsystem reliability requirements, then one may consider additive performance supports to increase subsystem reliability, sequence IV.

Automatic task performance implies that a machine generates or accomplishes whatever power, energy or energy transduction is required; a machine controls the application of the power or directs the utilization of the given energy. In automatic task performance man plays a more remote role. He may determine what is to be done, and perhaps how, as in the use of a digital or analog computer. He may set the limits for an automatic control like a thermostat. He usually monitors the output to determine that it meets certain minimal standards or is accurate. He initiates and may terminate the operation of the automatic device, as in the use of a record changer. Certainly he is responsible for preventative maintenance, repair and upkeep.

Activity 12. Allocate human performance development means. The purpose of this activity is to determine means for developing an adequate performance capability in system personnel. The direction and goals for such development means are provided by the studies made in activities 10 and 11. The inputs to activity 12 include information on:

1. Human performance required.
2. Range of performance values required.
3. Accuracy of output required.
4. Subsystem performance reliability required.

The first three inputs are from activities 10, 11 and 18. The fourth is from system analysis activities.

There are, in general, four ways in which one may develop performance means, through:

1. Personnel selection
2. Training
3. Job aids and manuals
4. Human engineering

Personnel selection techniques are useful when a small number of personnel are required, highly specialized skills are required, extensive experience is required, system personnel are to assist in system development and the system is essentially a one-shot attempt.

Training is a valuable technique when all of the performance requirements can be specified, a relatively large number of system personnel will be involved, system personnel will be a permanent or semi-permanent complement, skill requirements are relatively high but not specialized, extensive experience is not required and the system will have some long time duration.

Job aids and manuals will always be required. However, a particular kind of job aid - known as a Job Guide - is valuable in cases where the system is of long duration, there is relatively high personnel turnover, skill requirements are relatively low, task performance can be specified in detail and large numbers of system personnel are involved.

Human engineering can be used in two places. The first is to fit the equipment to the human being. This is what is usually meant by the term, e.g., type and arrangement of knobs and dials, working posture, work space arrangement and lighting, task sequencing, etc.

The second sense in which human engineering can be done is to modify the human emotionally and intellectually to help achieve the most reliable performance possible. Man is capable of learning, being motivated to perform well, adapting to changing conditions, developing attitudes toward specific work conditions and of changing his attitudes.

To date very little has been done to attempt to human engineer man, beyond attempting to motivate him through remuneration or discipline. For individuals who accept the social dictum that work is valuable in and of itself, there is no problem. All of man's experiences with respect to a system should be purposely designed to develop:

1. Positive attitudes toward system performance;
2. Positive motivation to achieve;
3. Motivation to maintain high reliability in the face of changing or degraded inputs;
4. Motivation to learn to adapt to changing or degraded inputs.

The output of activity 12 goes to activity 13, and to activity 14, sequence III.

Activity 13. Determine multiplicative performance support requirements. This final activity of sequence II is intended to develop all of the requirements to back up, assist and maintain multiplicative subsystem performance. The inputs to activity 13 come from activities 10, 11 and 12 of sequence II and from activity 18 of sequence III.

In general, performance supports fall into four broad categories:

1. Information processing, e.g., radar, computer, yaw-pitch integration, etc.;
2. Information presentation devices, e.g., displays;
3. Task performance, e.g., operational procedures, control wheel, key punch machine, etc.;
4. Communication devices, e.g., typewriter, telephone, radio, teletype, etc.

These can be expressed as facilities, personnel, equipment and material requirements.

The output of activity 13 goes to activity 25, sequence V, synthesis of support requirements.

## Sequence III. Maximizing Subsystem Reliability

The purpose of this sequence of activities is to maximize subsystem performance reliability. The activities of sequence III may be initiated as soon as there is an appropriate input from activity 12 of sequence II. The reason is that information about the reliability of multiplicative subsystems is necessary to determine the nature and extent of the requirement for additive subsystems to augment reliability.

Sequence III contains five activities:

14. Estimate human reliability for subsystem performance means;
15. Determine whether subsystem design concept meets reliability requirements;
16. Delineation of techniques for enhancing human reliability;
17. Consider techniques for enhancing human reliability;
18. Analyze impact of enhancement on performance development means.

The five activities of sequence III may be thought of as two relatively separate series, connected by a contingency. If it should be determined that a particular subsystem design concept meets the specified reliability requirements, activities 16, 17 and 18 may be omitted. In this case go directly to activity 23 of sequence V. If, on the other hand, the reliability requirements cannot be met, activities 16, 17 and 18 should be completed to attempt to augment subsystem reliability. If reliability requirements are still not adequate there are two choices. One may consider additives for reliability, sequence V, or one may discard the multiplicate subsystem design in question. If one chose to discard the given design concept, activity 3 would be begun again with an alternative design concept for that subsystem.

Activity 14. Estimate human reliability for subsystem performance means. The purpose of this activity is to estimate the reliability with which man will be able to achieve multiplicative subsystem performance. Activity 14 receives inputs from three other activities. From activity 12 comes inputs which:

1. Describe a human task, to be performed in a manual or a mechanized manner;
2. Determine subsystem reliability requirement from system analysis activities.

From activity 17, sequence III, may come a decision to consider the next alternative multiplicative design concept. Finally, from activity 21, sequence IV, may come an additive design concept for reliability evaluation.

This is one of the activities in which acceptance data can be of considerable value. Frequently alternative multiplicative performance means will be output from activity 12. Acceptance studies at this point may help to choose among these alternatives. This will afford the possibility of eliminating the unacceptable performance means prior to reliability determination. Work can be concentrated on the most desirable performance means. See chapter IV.

There are three ways in which human performance reliability may be estimated. The first and most desirable way of making the estimate is to consider the reliability of performance of the same tasks in other systems. Presumably, if man can perform at a given level of reliability in one system, he should be able to perform at a comparable level of reliability in another, where the same task and performance means are involved.

The second method is to make an "educated guess". This procedure involves looking at the kind of performance called out, inspecting human performance reliability in similar situations and then making a judgment as to whether or not the reliability requirement can be met. Such a judgment will ordinarily result in one of two conclusions: (1) no, because . . . . ; (2) yes, if . . . . .

A third way of estimating human reliability is to conduct a study specifically to estimate this value. The conduct of such a study requires that one isolate the factors which may effect human performance in the subsystem. Then an estimate is made of the range of values which these factors may be expected to assume in the subsystem. An index of human performance is decided upon. The factors which determine human performance are then built into an experimental design, or series of such designs, which will allow a determination of the effects of these factors and their interactions on the performance index. The study, or studies, are made and the results analyzed to elucidate human performance reliability. This is the most expensive procedure for estimating human performance reliability. However, if the experiments are adequately and carefully planned and conducted, it gives a reliable estimate of human performance reliability. Such an experiment frequently involves the use of simulated inputs and a mock-up of the task situation.

The output of activity 14 will go directly to activity 15.

<u>Activity 15. Determine whether subsystem design concept meets reliability requirements.</u> In many subsystems there will be a mix of manual or mechanized performance and automated task performance. In such cases

it is necessary to test the entire subsystem performance to determine whether subsystem reliability requirements are met. This requirement is a consequence of the fact that the term subsystem is ambiguous with respect to its reference. The performance entity which is considered to be a subsystem is dependent upon the boundaries which are determined for the system under development. If the subsystems under development are all unitary performance means, this activity is accomplished by completing activity 14. If, however, a subsystem includes multiple task units, as is the case in many information processing systems, activity 15 must be completed to determine whether all task performances operating in concert will meet subsystem reliability requirements.

The methods of determining whether subsystem performance meets the given reliability requirements are the same for activity 15 as for activity 14. The only differences are with respect to the experimental determination of subsystem reliability. In those subsystems which include sequential or serial task performance, the experimental designs which are adequate to estimate the effect of performance variables become quite sophisticated. This problem is compounded by the relative lack of available data to make estimates of subsystem performance reliability. The consequence of this is that one goes into a relatively expensive research program, or one ignores the reliability requirement and hopes for the best.

The output of activity 15 goes directly to activity 23 if subsystem reliability estimates are adequate to the requirement. If the subsystem reliability requirement is not adequate, the output goes to activity 17, to attempt to augment subsystem reliability by improving human task performance.

Activity 16. Delineation of techniques for enhancing human reliability. The purpose of this activity is to attempt to determine ways of improving human performance to help meet subsystem reliability requirements. It is recognized that an alternative route might be to require increased reliability of the automated subsystem performance. However, such considerations are beyond the scope of the present document.

The inputs for this activity come from those aspects of human behavior which are not shared with machines. Namely, the fact that human performance can be improved by:

1. Selection of individuals for task performance;
2. Motivating the individual;
3. Enhancing the flexibility and adaptability of the individual through training;
4. Modifying the attitudes of individuals toward techniques of task accomplishment;
5. Utilizing social mores to achieve task performance;
6. Human engineering or equipment changes.

The outputs of this activity go directly to activity 17.

One good way of enhancing human reliability, of course, is to insure that a given performance means has a maximally high acceptance value for its operators. Section IV describes methods of determining the acceptance value of a given performance means.

Activity 17. Consider techniques for enhancing human performance reliability. The purpose of this activity is to select techniques of enhancing human reliability which may improve subsystem performance reliability.

Inputs to activity 17 come from activity 15, i.e., the reasons for failure to meet subsystem reliability requirements, and from activity 16, i.e., techniques for enhancing human reliability.

The procedure here is to compare the two inputs from activities 15 and 16 to determine if the input from activity 16 can be utilized to alleviate any of the inputs from activity 15.

If it is possible to improve subsystem performance by techniques for enhancing human reliability, the path leads to activity 18. If it is not possible to improve system performance by enhancing human reliability one may consider:

1. Alternative subsystem designs;
2. Additive subsystem performance;
3. Automated subsystem performance.

Activity 18. Analyze impact of enhancement on performance development means. The purpose of this activity is to determine the effect on previously established performance development means, activity 12, enhancing human performance reliability, activity 17. If for example additional training is required to enhance reliability, the impact of this on the previously established training requirements and support considerations must be followed through and new training requirements and support established.

The input to activity 18 is the output of activities 12 and 17. The general procedure is to determine the effects of the method of enhancing human behavior on the means for developing human behavior, and then to update the means for developing human behavior in the given subsystem.

The output of activity 18 may be used in:

1. Activity 10 or 11, sequence II, to redesign multiplicative manual performance means;
2. Activity 12, sequence II, to allocate human performance development means;
3. Activity 21, to serve as an input to develop additive subsystem performance;
4. Subsystem analysis to determine additive subsystem requirements, constraints and reliability requirements;
5. Activity 18 to discard impractical multiplicative design solutions.

## Sequence IV. Additive Subsystem Performance

The purpose of sequence IV is to design the additive subsystems which will be required to achieve the given subsystem reliability requirements. The activities of sequence IV are the same as those of sequence II, since both sequences are concerned with the development of human performance means. A separate sequence was devoted to these activities in the presentation of the model because they are separate and sequential design tasks, necessitated by the failure of multiplicative designs to meet stated subsystem reliability requirements.

Since sequence IV and II are both concerned with developing performance means, their input-output relations are parallel, but not identical. Similarly, all of the remarks about the development of multiplicative performance means apply also in sequence IV. Here we will simply summarize these input-output relations. Sequence IV contains four activities:

19. Design of alternative feasible additive manual performance means;
20. Design of alternative feasible additive mechanized performance means;
21. Allocation of human performance development means;
22. Determination of additive performance support requirements.

<u>Activity 19. Design of alternative feasible additive manual performance means.</u> The inputs to activity 19 are the additive subsystem requirements and constraints, additive subsystem reliability requirements, human performance data, and activities 11, 17 or 18. The outputs of activity 19 are to activities 21 and 22 if additive manual performance means are feasible. If such performance means are not feasible the output is to activity 20.

<u>Activity 20. Design of alternative feasible additive mechanized performance means.</u> The input to activity 20 is from activity 19 with the addition of information about equipment capability data. The output of activity 20 is

to activity 21 and 22 if additive mechanized performance means are feasible. If such performance means are not feasible man may not play a local additive role. In such cases the performance may be achieved at a remote location, sequence VI, or automatically.

Activity 21. Allocation of human performance development means. The input to activity 21 is from activities 18, 19 and 20. Activity 21 output goes to activities 22 and 14, sequence III, maximizing subsystem reliability.

Activity 22. Determination of additive performance support requirements. The input to activity 22 is from activities 19, 20 and 21. The output is to activity 25, sequence V, synthesis of support requirements.

## Sequence V. System Performance Reliability

The purpose of sequence V is to estimate the over-all system performance reliability. The activities of sequence V are designed to achieve a system configuration with a maximum estimated reliability and then to test this system to estimate the actual system reliability. Such an estimate is required for trade-off considerations. Sequence V contains four activities:

1. Synthesis of manned subsystem designs;
2. Development of personnel requirements information;
3. Synthesis of support requirements;
4. Evaluation of system concept performance reliability.

The activities of sequence V constitute essentially a linear sequence. However, frequently a given activity can be started prior to the completion of a previous activity.

Activity 23. Synthesis of manned subsystem designs. The purpose of this activity is to bring together all of the manned subsystems as a first approximation of man's role in the local system. This approximation will be incomplete for the over-all local system to the degree that automatic subsystem performance is necessary. If no automatic performance is required, this will be the first model of the complete system.

The inputs to activity 23 are from activity 15 or 18 of sequence III which include:

1. Performance requirements specification for each subsystem;
2. Performance means for each subsystem;
3. Estimates of performance reliability for each subsystem.

In addition, the system reliability requirement is known from system analysis activities.

The procedure in activity 23 is known as the allocation of reliability to subsystem performance. Mathematical techniques are utilized to estimate system reliability from known subsystem reliabilities (7). This estimated system reliability is then contrasted with the system reliability requirement to determine its adequacy. The estimated and the required system reliability should be the same, within statistical limits of error. If the estimated and required system reliability are not the same, within the statistical limits of error, it is necessary to reallocate reliability among the subsystems to enhance the estimated system reliability. Reliability may be reallocated by:

1. Selecting performance means with a higher reliability to replace those with a lower reliability;
2. Selecting performance means with a higher reliability to replace those with an adequate reliability, when the first alternative fails.

It is possible to estimate the least reliability which any subsystem can possess and still achieve the required system reliability (6, 7). By thus adjusting back and forth among the subsystems it is possible to maximize estimated system reliability.

The output of activity 23 is to activity 24.

Activity 24. Development of personnel requirements information. The purpose of this activity is to develop the manning requirement for the system. The input to activity 24 is the multiplicative and additive subsystem designs and human roles from activity 23.

The procedure here is to analyze subsystem performance means to determine:

1. The time required to complete the performance;
2. Frequency of performance;
3. The sequencing of performance over time;
4. The coincidence of performance in time.

The result of this analysis can be used to estimate manning requirements and develop a preliminary work-rest cycle.

At this point it should be noted that all of the activities of the first four sequences have been performed without any consideration of manning requirements. If a single operator is all that is required, the output of activity 24 can go to activity 25. However, if multiple operators are required, it will be necessary to go back and review the effects of using multiple operators on activities 8 through 24. It is necessary to determine the effects of multiple manning on:

1. Support requirements for local stress compensation, activity 8;
2. Support requirements for local multiplicative performance, activity 13;
3. Support requirements for local additive performance, activity 22;
4. Support requirements for remote performance, activity 31.

The output of this activity feeds directly into activity 25.

Activity 25. Synthesis of support requirements. The purpose of this activity is to organize and coordinate all of the support requirements for manned subsystem performance. There are four general categories of such support requirements:

1. Facility
2. Equipment
3. Personnel
4. Materials

The input to activity 25 is from activities 8, sequence I; 13, sequence II; 22, sequence IV; 24, sequence V; and 31, sequence VI. The output from activity 25 is directly to activity 26.

Activity 26. Evaluation of system concept performance reliability. The purpose of this activity is to make an estimate of the completed local system performance reliability. The input to this activity is from activity 25. In addition, estimates of reliability requirements for unmanned subsystems from systems analysis are required. There are three different techniques which may be used to make the required estimate:

1. Probability estimates of system reliability from subsystem reliabilities;
2. Computer simulation estimates of system reliability, e.g., Monte Carlo or linear programming techniques;
3. Physical simulation, the use of simulated inputs to test human performance reliability in mock-ups of the task situations.

Which one, or combination, of these methods is chosen depends upon the constraints of time and money which are placed on system development. In general, going from method 1 to method 3, the cost in time and money increases. Method 1 is least desirable since it is purely an analytic technique. There is no way to consider the variability or distributions of performance variables, or the frailties of human performance.

The use of computer simulation to estimate system performance reliability requires a knowledge of the mathematical functions which describe system performance. This is a distinct disadvantage in systems which utilize manual performance. With the exception of certain simple tracking tasks, attempts to describe human performance by the use of mathematical techniques tend to be after-the-fact activities with little generality. Further, if the input to the system is changing or noisy, the result of such a technique can be very misleading. Computer simulation techniques are best used where human performance is not an integral part of system performance, i.e., the human is a passive recipient of action. Examples of such things are hospital loading problems, cueing problems, estimating down time and spares requirements for an essentially static system, etc.

The third method, physical simulation, requires the greatest amount of knowledge about system performance. At the level of development to which the present document is addressed, it is unlikely that this method could be used, except with isolated system tasks. In this case, however, physical simulation offers the advantage of allowing potential operators to participate in system development. This, however, is not the problem of the present section.

The output of activity 26 is to trade off activities if the estimated performance reliability is adequate. If performance reliability is not adequate, then one may consider alternative system concepts. If there are no alternative concepts then one may consider either a modification of the system reliability requirement or automatic performance.

## Sequence VI. Remote Subsystem Performance

The purpose of this sequence is to develop requirements for remote human roles, which parallel the requirements for local human roles developed in sequence I. The question is whether man can be utilized in a remote multiplicative role or whether he may play only an additive role. The development of remote human roles need not await the development of local roles. Subsystem requirements and constraints will delineate certain roles for remote locations. On the other hand, the final requirement for remote roles cannot be specified until the determination of local roles has been completed. The remarks made in the introduction to sequence I apply here.

Sequence VI contains six tasks:

27. Delineation of remote system ecological requirements and constraints;
28. Analysis of remote system/ecological requirements compatibility;
29. Development of compensation techniques for remote system;
30. Delineation of remote system anthropometric requirements and constraints;
31. Determine support requirements;
32. Determine if man is mandatory.

Since the activities of sequence VI parallel those of sequence I, and since the discussions of sequence I apply here also, the discussion of sequence VI will be limited to a description of input-output relationships.

Activity 27. Delineation of remote system ecological requirements and constraints. The purpose of this activity is to determine the ecological characteristics of the remote performance environment. The inputs required are the multiplicative and additive subsystem requirements and the system ecological considerations from activity 3, sequence I. The output from activity 27 goes to activity 28.

Activity 28. Analysis of remote system/ecological requirements compatibility. The purpose of this activity is to determine the nature of the support and protection which will have to be provided if man is to participate in a remote role. The inputs required are the remote subsystem performance requirements and the output of activity 27.

The remote subsystem performance requirements are determined by considering those tasks which must be performed remotely in conjunction with the inputs from activities 11 and 20. These latter specify further subsystem performances which can be accomplished remotely.

The output of activity 28 is dependent upon the results of the analysis. If the remote system environment will not place stress on any ecological variable, the output is to activity 32. If any ecological variable will be stressed, then an output must go to activity 29.

Activity 29. Development of compensation techniques for remote system. The purpose of this activity is to determine the methods to be used to protect man when the system environment stresses any ecological variable. It should be emphasized that the remote system, by definition, can protect and sustain man and, therefore, there is no option in the output for situations where man cannot be protected. The input to activity 29 is the output from activity 28 which specifies the nature of the ecological incompatibility and the subsystem performance involved. The output of activity 29 is to activities 31 and 32.

Activity 30. Delineation of remote system anthropometric requirements and constraints. The purpose of this activity is to determine the requirements which will be placed on the system if man is to play a remote role. The input to this activity is the multiplicative subsystem performance requirements and constraints, the additive subsystem performance requirements and constraints and the output of activity 1, sequence I - anthropometric system considerations. The output of activity 30 is directly to activity 31.

Activity 31. Determine support requirements. The purpose of this activity is to specify the kinds of things which will be required to back up, assist and maintain human performance in the remote roles. The inputs to activity 31 come from activities 29 and 30. The output of activity 31 is to activity 25, sequence V, synthesis of support requirements.

Activity 32. Determine if man is mandatory. The purpose of this activity is to determine if it is necessary for man to play a remote role in the system. The discussion associated with activity 7, sequence I, applies here also. The inputs to activity 32 are the outputs of activities 28, 29, and 6, sequence I. The output of activity 32 is to activity 10, sequence II, design of alternative feasible multiplicative manual performance means.

## Data Requirements

The present model for determining the role of man in a system calls for data from fifteen different sources. These sources and the sequences in which the data are used are summarized in Table 1. Data classes 1 through 6 are independent of any particular design configuration. However, the degree of use of any data item from these classes is dependent upon the specifics of the design configuration. This is the reason for including data classes 7 through 15 in the table. The specific items in these data classes (7-15) are directly dependent upon the system configuration. Further, they determine which of the data items in classes 1 through 6 will be pertinent.

Table 1. Data classes required to determine the role of man in any system, and the sequences in which these data are used.

| | SEQUENCES | | | | | |
|---|---|---|---|---|---|---|
| | I | II | III | IV | V | VI |
| 1. Anthropometric data. | X | | | | | |
| 2. Ecological data. | X | | | | | |
| 3. Protection and sustenance data. | X | | | | | |
| 4. Human performance data. | X | X | | X | | |
| 5. Unique human capability data. | | | X | | | |
| 6. Equipment capability data. | | X | | X | | |
| 7. System configuration. | X | | | | | |
| 8. Multiplicative SS* requirements and constraints. | X | X | X | | | X |
| 9. Multiplicative SS reliability requirements. | | X | | | | |
| 10. Additive SS requirements and constraints. | | | X | X | | X |
| 11. Additive SS reliability requirements. | | | | X | | |
| 12. Remote SS requirements and constraints. | | X | | X | | X |
| 13. Remote SS reliability requirements. | | X | | X | | |
| 14. Mechanized SS design reliability. | | | X | | | |
| 15. Unmanned SS reliability requirements. | | | | | X | |

*Subsystem

# IV. ACCEPTANCE

Man-machine system design has typically utilized data as to man's sensory, perceptual, cognitive and motor capabilities in allocating functions to man or machine, and in designing interfaces. However, man's motivational system (i. e., acceptance) has not been systematically included in man-machine system design. This is a serious error as a highly motivated man can compensate to a considerable extent for poorly designed equipment to maintain system output. Conversely, a man dissatisfied by a machine function, due to status, economic, or survival fears, or simply a desire to perform the function manually, because it is a function man enjoys, may not properly use equipment which has been designed to fit all other criteria. Consequently, the system output may suffer. Acceptance factors are most critical, and will have a maximum effect on system effectiveness, in the role area. As the design of man's role is a major output of System Design, or effort IV (see Figure 4, page 13), it is most important to include acceptance factors at this point. Acceptance factors should also be considered at the later design efforts, but they become less and less critical as Task Design, or effort VIII, is approached.

Acceptance problems could be defined as any frustration of any human need. It is not necessary, however, to consider all unmet human needs. The purpose of the model being developed is to increase the efficiency of the man-machine system design process, not to make an academic contribution to the theory of motivation. Consequently, it is only necessary to add to system design some methods for delineating and preventing acceptance problems which are not resolved by current techniques. For example, sexual deprivation occurs in many manned systems, and is a need frustration which could be considered an acceptance problem. However, the possible effects of human need frustration due to the system environment, including sex frustration, are always considered in system design, and do not need to be pointed out again. The neglected acceptance problems, which need additional techniques to be resolved, are in the areas of role development and the means for obtaining and maintaining human capability. The acceptance problems with which the present approach is concerned are those man-machine interactions which do not satisfy human expectancies as regards mode of performance, social status, economic status or perceived survival probability.

The data and conclusions reached from the use of the methods described in this section should be fed into the model in sequences II, III and IV. These data would be an input to the design of alternative multiplicative manual performance means, activity 10, and alternative multiplicative mechanized performance means, activity 11, in sequence II. Similarly, the acceptance data would be an input into the design of additive alternative manual and mechanized performance means, activities 19 and 20. Acceptance data should then be fed into activities 16, 17 and 18, in sequence III, to increase subsystem reliability.

## Current Acceptance Problems in Man-Machine System Design

Automated functions. - Automated systems are man-machine systems in which some tasks are performed by machines. These systems all include manual tasks, although they may be performed at a remote time or place. Where man is a system component, he must be designed into the system in an optimum manner, like any other system component.

Current automatic methods for implementing tasks frequently do not solve the problems they are designed to solve, and, in fact, create new problems. For many years to come automated systems will be man-machine systems that, at a minimum, will require man to initiate the machine functions, monitor them, and decide when to disengage and override them. However, if all man-machine interfaces are not optimum, system effectiveness cannot be optimum, as the system will be under-used and/or used improperly, either covertly or overtly. Traditional human engineering, usually performed after the system has been designed and the breadboard equipment developed, has been applied as if man were rational and it were only necessary to consider such aspects of man as his perceptual and motor capabilities. In actual fact, however, it is equally important to consider man's fears, anxieties, aspirations, etc., as part of the design efforts.

Acceptance problems created by lack of confidence in the effective and reliable performance by hardware of automated functions must be considered independently of whether in fact the hardware is effective and reliable.

What is necessary is the utilization of data on human attitudes toward the automation of specific system functions and how they are automated. This information must be used when man or machine function allocation decisions are being made. This will permit the incorporation of acceptance factors as additional criteria in trade-off analyses, which already include a consideration of the performance capabilities, costs and reliabilities of man and machine components. It may be found, for example, that a decision to automate a particular system function based upon sound engineering considerations would produce a degree of negative acceptance that would clearly offset the anticipated advantages of the engineering solution. These cases should be systematically identified in a manner which would provide for a timely consideration of their importance, i. e., prior to the final specification of the system configuration. Where trade-off analyses which include acceptance criteria indicate a machine allocation and means of implementing machine automation that will result in substantial nonacceptance, other methods for increasing acceptance need to be introduced. This is not as radical an innovation as it sounds. After all, we are using man as a system component. And we would not use a hardware component that would reduce the reliability of other hardware components without considering alternative designs, or taking steps to restore the reliability of the second component.

Skill maintenance and development. - The morale of man is frequently lowered if he is not functioning at what for him is a high skill level. Aristotle defined happiness as functioning at the highest level one was capable of. More recently, Nissen (69) in his paper on motivation stated that "Capacity is its own motivation". Consequently, if a man's system role does not permit him to exercise his capabilities, or capacity, he will become frustrated and lose motivation for performing his assigned and expected system tasks. As Firstman and Jordan (30) pointed out:

> The problem of maintaining skills has many psychological ramifications. A highly skilled person is "insulted" if he is given a task that does not call for his using these skills. He has invested much time and energy in achieving his highest skilled performance and takes pride in it. People like to "show" others and see for themselves that which they take pride in. They expect to be able to do it in their job; being unable to do this is very frustrating. This frustration is aggravated by the awareness that the job does not permit them to keep the skills they acquired with so much difficulty. . . . So far as possible, equipment should be so designed that men of various proficiency levels can use it effectively. For example, both a novice and a highly skilled technician use meters; the difference being what they can do with meters. This "open-end" demand on the skill of a novice operator motivates him to increase his proficiency, and, as a by-product, makes him readier and more able to improvise and solve problems in times of emergencies.

The frustration of desires to exercise and maintain one's skills is a serious and common problem. An example is the very infrequent use on commercial airliners of the ILS-Autopilot Coupler, which was designed to make automatic landing approaches under low visibility conditions, and thereby permit the pilot more time at this critical point in landing for monitoring and scanning, by relieving him of the tedious servo task of staying on the radio beacons. In a study in which the non-use of this equipment was investigated (91), it was noted that a frequent explanation given by the pilot for not using this automatic equipment was that they needed to fly the plane themselves, during the low visibility conditions in which the ILS-Autopilot Coupler should be used, in order to maintain their proficiency.

This problem of not being permitted to maintain and improve a skilled capability can become compounded by an expectancy problem. Frequently, a man will be led to believe that he will function and learn at a higher level than in fact he will on the job. This false expectancy, often the result of overly zealous recruitment, will increase the frustration due to non-use of complex skills. We recently investigated an acute military morale problem. It was found to be due to the non-use, on the job, of the complex skills acquired before field assignment. The training which was received was designed to prepare men to devise procedures for solving problems as they occurred. However, the men found upon arrival in the field that they had to follow detailed written procedures in the performance of all their tasks. They were not allowed to deviate in any way from these procedures or to devise new procedures to deal with problems as they occurred. The false expectancies created by the recruitment and training program aggravated the frustrations produced by non-use of complex skills and the lack of opportunity to learn new skills, resulting in a severe morale problem.

It is apparent that the majority of people are motivated to use what are for them their highest level skills, and to develop new skills. High level skills are, for the individual, those that tax his abilities more than others, and those that place him in a higher relative status position compared to his associates than do his other skills (see reference 28 for a review of the research on morale, and the status factor). If this motivation to use and develop high level skills is frustrated morale drops, and in a man-machine system the man may attempt to circumvent, or refuse to perform his programmed functions, as has occurred with the ILS-Autopilot Coupler.

It may be noted, however, that there are some people in every situation who do not wish to perform at a more complex level. Furthermore, there are times and situations in which all of us wish to perform at a level of complexity or skill below our maximum, as in some forms of relaxation and play, in non-critical situations, when we are tired, etc. However, this model is being prepared for vulnerable systems, such as aerospace vehicles which will operate in unusual environments for extended periods of time far from sources of support. When man is assigned a local role in such a system, one of the primary reasons, as discussed in section II, is so that he can solve unforeseen problems when they arise. This performance requirement will in turn require the kind of man who is frustrated by, and finds unaccepting, roles that do not maintain and even challenge his abilities. However, where the system requirements do not require man for solving unexpected problems, it will be possible (as discussed below) to consider the use of those who do not find routine, non-challenging jobs unacceptable.

## Acceptance Principles and Data

The system designer seeking acceptance data for use in the model described in section III can utilize the following principles, data sources and methods.

Current knowledge. - Unfortunately, little work has been done on acceptance problems in system design. However, the previous work on this contract on acceptance of automated flight control techniques by pilots produced some principles that may be generalizable to other systems. However, it should be remembered that these were developed on this one specific system.

Acceptance of automated functions. - The work on acceptance factors in automating all-weather landing produced the following principles:

(1) The more system experience a man has, with this experience including exposure to automated equipment, the more accepting he is of the automated equipment and the more he will use it in the prescribed manner.

(2) Those with more status, responsibility and authority tend to be more accepting of and make more use of automated equipment than others.

(3) Where failure of the performance of its function by automated equipment can endanger the life of the man, he is less likely to accept and use it despite prescribed procedures.

(4) There is generally high acceptance, within the limits of the above three principles, of the automation of servo tasks, particularly those which must be performed over long periods of time.

(5) There is generally rather low acceptance of automation of decision making functions.

Role of man. - The work performed on the automatic landing acceptance problem and the study of morale problems in a military unit revealed the following three principles regarding acceptance of the system role of man.

(1) Men are generally accepting of systems roles which give them an opportunity to exercise and, therefore, maintain skills which they feel are important to maintaining their position in the occupational and social status system in which they are immersed.

(2) Men are generally accepting of system roles which permit them to vary their procedures and the manner of accomplishing their tasks, on their own initiative. Roles that fail to permit man to vary his procedures on his own are generally labeled mechanical.

(3) Men are more accepting of roles which permit them to learn. In a recent study (unfortunately, utilizing a sample of only seventeen) a correlation of +.61 (statistically significant at the .01 level of confidence) was found between how much the men felt they were learning on their job and their intentions to re-enlist.

The literature. - Although there is undoubtedly insufficient information available that is applicable to acceptance problems in system design, it is also certain that there is some useful information. The problem is that the information in the literature has not been surveyed and classified in a usable manner for avoiding acceptance problems in system design.

Probably the largest source of data would be found in the academic disciplines of industrial psychology and industrial sociology. The data in studies on morale, stress, motivation, communication, human relations, and on small groups should be surveyed and abstracted for this purpose. However, data from the academic disciplines is often based on research performed with college students as the subjects. Data based on college students must be used with caution. Such data is frequently not applicable (generalizable) to normal work groups or military situations (see reference 89).

A better source of relevant data would be applied reports, such as those that can be obtained through NASA or ASTIA on problems in automation. A good source of this type of data are the documents produced by the Air Force in their personnel subsystem test and evaluation (PSTE) programs.

Empirical methods. - Where information is not available in the literature, and/or where the above principles will not provide the required design tolerances, it may be necessary to obtain data empirically on specific system problems. Where this is the case, the methods developed on the current project on the all-weather landing problem can be utilized.

Acceptance data can be collected by questionnaire or interview. The procedure is to describe the system being developed in terms of each of its functions, and the available means for implementing each function. A sample of ultimate operators or users (manual components) of the system can then be asked to state their acceptance attitudes toward each means, including both automatic functions and manual roles, and to make any additional comments they may have. This procedure can and has resulted in the suggestion by operators of effective means previously not anticipated.

This research method requires the four major steps of developing the instruments, identifying the sample, administering the instruments, and interpreting the data.

Developing the instruments. - It is first necessary to recognize that the information available on a system under development is always in an R&D language which is likely to be unfamiliar to the general user population. In addition, the information will contain code words, terms and phrases not even known by experienced aerospace scientists and engineers who have not worked on the system in question. Consequently, it will be necessary to first translate concepts and descriptions into a more common language. For the purpose at hand it is necessary to translate, rather than to define the code in use, as is frequently done, as such definitions become tedious and lengthy and tend to exhaust the interest of the subject.

A second and more serious problem is that the future manual components (operators) will usually be unfamiliar with many of the system concepts and automatic techniques being considered. Consequently, they will be asked to state opinions about something unknown to them. If, in an attempt to solve this problem, they are given a statement as to what the system will be like, it is apparent that their answer will then be a restatement of the information given them. For example, if asked to assume a highly reliable automatic system function they may say there is no problem (if it really is very reliable). And, of course, if told that the automatic function will not be reliable, then they will say they did not want it in the system. It is apparent that this problem will occur whenever acceptance criteria are to be included in trade-off decisions. It is also apparent that operators generally are not sufficiently familiar with research and development methods or with engineering principles and hardware to provide a meaningful reaction to technical decisions regarding methods of implementing automatic functions.

A solution to this problem is to use a two step method for obtaining acceptance data. The first is at a general level to obtain meaningful and quantifiable data from operators as to their attitude toward proposed manual roles and automatic functions. This can be accomplished by a questionnaire developed on the assumption that the average operator is not really concerned with nor qualified to give opinions on how a specific black box performs its function. Rather, they are concerned with what functions will be automated, what functions are manual, how they will perform and learn to perform the manual functions, and the interface between manual and automated functions. Furthermore, they are concerned with displays for monitoring automated functions, displays for assisting them in manual functions, and they are very concerned with and have useful opinions on back-up systems. They are particularly concerned with the manual back-up system which is often assumed, even in the most fully automatic systems (or the operator would not still be there). For purposes of manual back-up, they want to know when they will have to assume control in case of a malfunction, how they will detect a malfunction, how many degrees of freedom are remaining at this point, etc. It is clear, therefore, that very meaningful information at this level can be obtained without operators knowing or being given extensive technical information on developmental techniques.

In addition, acceptance attitudes regarding an analogous system or subsystem should be obtained. Although industry is constantly developing new systems and subsystems, this is really an evolutionary process, and it is possible to identify an analogous system or subsystem known to the subjects which will provide predictive attitudinal data.

A funneling technique is best for questionnaire development. This method consists of beginning an investigation of a problem at the widest and most inclusive possible level, using unstructured methods for obtaining information, i. e., free discussions with available subjects selected without any attempt to rigorously define the population. The information gathered by this method permits the development of more structured interview schedules, thus beginning to narrow the field of information to be investigated as more is learned about the acceptance problem and its boundaries.

An interview schedule should be developed simultaneously, as the second step, for use with those more familiar with some of the system concepts and techniques under consideration. These individuals can give more specific attitude data, as well as provide critiques of proposed means. An interview rather than questionnaire should be used because of the complexity of the questions and information required.

Sampling. - The subjects used in the acceptance study should be representative of those who will operate and maintain the system after development, although it is helpful to utilize the R&D and special cadre personnel involved in system development for the interview sample. They can give meaningful critiques of proposed means, both manual and automatic, for implementing functions and tasks. However, for obtaining acceptance data, per se, on automatic and manual means, it is necessary to use subjects who are representative of those who will use the system. These representative subjects are best obtained by random sampling. It may be desirable to also stratify the sample, in order to obtain additional information, or because of the complexity of the subject universe.

Opinion leaders should also be identified and sampled, as the differences in attitudes between them and the rank and file will help predict the likely direction of change in attitudes following system installation.

Administering the instruments.- Subjects should be guaranteed anonymity as individuals to encourage full and honest responses. They will not object to the revealing of group averages, which is the desired information.

Mailed questionnaires should not be longer than five pages, or too few will be returned. An interview schedule can be a few pages longer, as the interviewer can help maintain interest.

A follow-up, individually addressed letter should be sent to increase the number of returns. It is preferable to obtain a large percentage return, on a small sample, rather than a larger absolute return on a larger sample, i.e., it is the percentage of return, not the number (over, say, thirty or forty) that is more important.

Analysis of the data.- Two sources of possible error in questionnaire data should be checked first. These are:

(1) A major problem is the possible distortions in the data because of the unknown attitudes of those whose questionnaires are not returned. It is possible to approximate an answer to this question, i.e., what are the attitudes and opinions of those who did not answer their questionnaires, at least qualitatively if not quantitatively. The sample should be divided into three groups, those who responded immediately, those who responded only after being prodded by the follow-up letter, and those who did not respond at all. It is reasonable to assume that on questions where those who responded quickly and those who responded only after prodding do not differ significantly in viewpoint the non-responders likewise will not differ significantly in viewpoint. However, where there are differences between those who responded quickly to the questionnaire and those who only responded after prodding, it may be assumed that the attitudes of the non-responders are even more divergent from the early responders than are those of the late responders. This probability should be used as a corrective factor in the interpretation of the data.

(2) A second problem is that of validity, i.e., can data obtained about something that does not yet exist (at least in the experience of the subject) predict the attitudes which will prevail toward it when it does exist? To check this, attitudes toward the extant, analogous system or subsystem should be correlated with those given for the new system. A significant relationship will indicate that some confidence can be placed on the predictive value of the data. A lack of significant positive relationship would indicate that further investigation was needed before the data could be relied on (e. g. , were the subjects giving distorted data to influence management?).

## Methods for Increasing Acceptance

### Non-acceptance of automation. -

Re-allocation. - If a serious acceptance problem exists which will lower system effectiveness, a re-allocation can be made, with the subsystem or functions producing the acceptance problem changed to manual, providing this change will improve over-all efficiency.

Additional displays or controls. - Frequently non-acceptance of automation could be greatly reduced, if not eliminated, through the use of additional hardware, which hardware would not be necessary on grounds other than the acceptance problem. The feasibility of this type of solution was apparent in earlier research on this contract (see reference 78) on the resistance of pilots to automating certain landing functions. Pilots frequently would state that they would not accept automation of some landing function, but when asked if they would accept such automation if they had a display for monitoring the function they stated that this would make the automation completely acceptable. Additional displays for monitoring and thus providing understanding of what is occurring while automatic functions are being performed is obviously the most likely additional hardware technique for reducing non-acceptance of automation. However, there may be cases in which additional controls could also improve acceptance.

Training on automated functions. - Man may often not have been given sufficient training to understand how many automatic functions are performed, because there was no requirement for such training. However, if an acceptance problem exists regarding such automated functions, it may be that training in how they are performed, the theory behind them, and their reliability will build confidence in them and, therefore reduce the acceptance problem. The purpose of such training would only be to improve acceptance, and it should be designed accordingly.

Practice. - In earlier work on this contract, in a study of acceptance of the ILS-Autopilot Coupler (reference 91), it was found that the more system experience (i.e., flying hours) a pilot had the more accepting he was of the ILS-Autopilot Coupler and the more he used it. This suggests that the acceptance of automated functions might be increased by giving operators experience in the system in a controlled environment during their training, either through the use of simulators or real hardware. Consequently, when they became part of the system in its intended environment they would be more adapted to the automatic equipment and, therefore, less inclined to tamper with it or in other ways negate its effectiveness.

Attitude change techniques. - There are several powerful ways to change attitudes (see reference 90) which, in some cases, could reduce the acceptance problem. The use of such techniques would probably not generally be desirable, because of the consequences of being seen as manipulative. However, where other data indicated that experience with the system would later reduce the acceptance problem to allowable levels it might be justifiable to use attitude change techniques to bridge the experience gap.

Selection. - The attitudes of men toward machines varies rather extensively, with some people quite anti-machine and others very pro-machine and pro-automation, with many gradations and individuals in between these positions. These individual differences in attitudes toward machines could be utilized where there would be a general acceptance problem with machine automation to select individuals who would accept this allocation. Some work has already been done on developing a scale for measuring attitudes toward computers (see reference 51), which scale could undoubtedly be modified to include acceptance attitudes toward automation in general.

<u>Non-acceptance of man's assignments.</u> -

Selection. - Where it is necessary or more effective to utilize man in a manner which will create an acceptance problem with most men, it may be possible to utilize selection to avoid the acceptance problem. For example, a common problem is the necessity to use man in a mechanical, routine manner which frequently produces an acceptance problem. However, it is possible through careful selection of those who will not be offended by such tasks, and the control of job expectancies, to minimize or even completely avoid this problem, providing that all the tasks in the position will be consistent with this lower level selection requirement. A frequent mistake in designing man into systems is over-selection and over-training, which results in the system tasks being seen as dull and frustrating. If selection, training and job expectancies are more consistent with actual job requirements and realities, motivational problems of this type will not be produced.

Re-allocation. - In some systems it would greatly improve acceptance if the functions were re-allocated so that the manual roles would be more challenging. This follows from the study, mentioned above, in which a high correlation was found between a man's feeling that he was learning on the job and his intentions to remain in the military service.

Re-allocation of tasks. - In some cases acceptance problems could be removed through re-allocating tasks between man and machines to eliminate unacceptable manual roles. For example, systems sometimes have repetitious tedious tasks which for economic reasons have been assigned to man. However, it may sometimes be the case that if these tasks were automated it would improve morale and efficiency, and personnel retention, sufficiently to offset the cost of automation.

Additional tasks. - In some cases acceptance of the manual roles and tasks could be improved through the use of additional tasks, in a manner analogous to the discussion above in which additional hardware would be added to the system in order to improve acceptance. For example, it would frequently, if not always be possible to add as tasks the learning of system theory, concepts and relationships. These learning tasks would be added to the subsystem only for purposes of improving acceptance and morale, not for providing necessary capability. Consequently, the learning tasks should be designed accordingly, i. e., they should be interesting and challenging, but within the aptitude levels of the men for mastery by them.

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# APPENDIX: DATA REQUIREMENTS

## Introduction

The model for determining the role of man has called out certain requirements for data. It is the purpose of this appendix to illustrate the usefulness of the model for determining the scope of data requirements; the breadth of availability of these data; and the organization which is suggested by the model. There is, in fact, a large amount of data on human performance. Serendipity Associates has made no effort to be inclusive. There are two reasons. First, neither the time nor the funds were available. Second, it is felt that neither Serendipity Associates nor any other single organization is adequate to do the total data compiling task. This task will require a large staff of highly diversified subject matter specialists.

This appendix is in three parts. The first deals with human ecological requirements and constraints, to provide data for activity 3 in sequence I, delineation of human ecological requirements and constraints, (see Figure 10). The second provides data for activity 6, also in sequence I, on human capability to perform sensory and motor tasks. The last part of the section deals with man as a system component, considering his limitations, where he excells, the conditions under which man is a required system component and techniques for enhancing human performance. These data are also necessary for the performance of activity 6, in sequence I, as well as for activity 17, enhancing human reliability, in sequence III.

## Human Ecology

Introduction. - Ecology is the study of the relationships among organisms and between them and their environment. The term is used in the sense of antecology -- the relations between the individual organism and its environment. The ecological relations between an organism and its environment define the range of climatological, sustenance and protection factors which limit the ability of the organism to exist and function in a given environment.

In general, ecological factors tend to place limits on man's ability to perform. For example, as man increases his altitude above sea-level, the amount of oxygen received per breath decreases. After passing a given altitude, which varies with untrained individuals from 10-15 thousand feet, there is a general loss of the ability to perform tasks, both mental and physical. Frequently, the individual is unaware of this effect. A general feeling of well being exists which is called euphoria.

A second characteristic of ecological factors is that, within limits, the human body can adjust to deviations from what might be considered a normal, or perhaps optimal, range of values. To continue the example of oxygen deprivation, humans are found at altitudes in excess of 17 thousand feet in the Andes Mountains of South America. These individuals suffer no oxygen deprivation. Indeed, with training in a pressure chamber the natives of Morococha, Peru, attained an average critical altitude of 31, 000 feet. The time of useful consciousness (TUC) for these individuals at 30, 000 feet exceeded one and one half hours. At 40, 000 feet TUC was reduced to one and one half minutes (8). These individuals have a much higher red blood cell count than do humans living at sea-level. Thus, their bodies adapt to the relative oxygen scarcity by increasing the number of red cells to make more efficient use of the total available oxygen. If a sea-level person visits these remote altitudes, he can, after a period of time, adjust to the relative oxygen deprivation. His red cell count will increase to approximately that which is normal for the natives of the area. If this individual then returns to sea-level and remains there for some period of time, his red cell count will drop to the normal range for individuals at that altitude.

As a final example of the interaction between ecological factors, consider human metabolism. Human metabolism may be viewed as a vector quantity which is dependent upon such factors as task activity, temperature, available oxygen, the state of alertness and fatigue, anxiety or fear, respiration, cardiovascular integrity, hormone balance, the digestive state, toxic intake (smoke, gases, chemicals) excretory functioning, fluid and electrolyte balance. All of these factors will be affected, directly or indirectly, by the environment of the individual. The metabolic state, in turn, determines quantitative and qualitative food and water intake, as well as the quantity and quality of eliminated waste products (76).

The role of environment. - The demands which the individual places on his environment may be classed as physical, physiological and psychosocial. Among the physical constraints one may list:

Temperature control;
Humidity control;
Illumination control;
Communications means;
Protection from discomfort;
Protection from danger;
Potential for emergency escape.

Among the physiological constraints one may list:

Provision for potable water;
Provision for nutritive substances;
Breathing gases, oxygen, nitrogen, carbon dioxide and water balance;
Ventilation;
Movement and exercise;
Accommodation of the human diurnal cycle;

Sanitation and bodily cleanliness;

Waste disposal, urine, feces, sweat, flatus;

Detection of long range aberations in respiration, digestion, cardiovascular function, indocrine function, metabolism, dermatological changes;

Treatment for trauma and disease.

Among the psycho-social factors one may list:

Neurological stability;

Emotional stability;

Mental stability;

Maintenance of motivation;

Maintenance of alertness;

Provision for ingesting water and food;

Acceptance factors in waste disposal.

From the point of view of the physical and physiological factors, the ideal environment would have the characteristics listed in Table 1.

Table 1. The ideal human environment.

| | |
|---|---|
| Temperature | $68\text{-}72^{\circ}$ F. |
| Relative humidity | 40-50% |
| Ambient pressure | 14.7 psi |
| $O_2$ partial pressure | 18-21% |
| $CO_2$ partial pressure | 0.3-0.5% |
| $H_2O$ daily intake | 5 lbs. |
| Ozone and atmospheric polution | Zero |
| Nuclear radiation | <40 mr/day |
| Ambient illumination | 5 millilamberts |
| Ambient random noise | 20 db |
| Maximum noise level | 120 db, $2 \times 10^4$ dynes/$cm^2$ |

| | |
|---|---|
| Air movement | 100 $ft^3$/min |
| Clothing | shirt sleeves |
| Minimum operational space | 650 $ft^3$/man.* |

Table 2 presents the approximate number of pounds of food, oxygen and water required for the indicated number of men for excursions of varying time periods (modified from 76). It is possible to extrapolate to a larger crew by multiplying the given figures by the number of crew members. It should be noticed also that table 2 assumes a linear relation between the duration of the excursion and the quantity of food required. In an actual instance, this will be a function of the ages of the crew members and the quality of the food as well. It further assumes that crew members will actively seek to maintain their bodies in a healthy state.

Table 2. Approximate number of pounds of food, oxygen and water for one man for excursions up to 3 years.

| Duration of Excursions | | Pounds of Food |
|---|---|---|
| Days | Years | |
| 1 | .0027 | 6.3 |
| 5 | .0137 | 31.5 |
| 10 | .027 | 63.0 |
| 182 | .5 | 1,150. |
| 365 | 1.0 | 2,300. |
| 730 | 2.0 | 4,540. |
| 1095 | 3.0 | 6,840. |

Given a certain food and water intake, table 3 presents the daily metabolic turnover of the human adult who performs light work (19).

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* This factor will be a function of the nature and duration of the system mission and the role which man plays in achieving that mission.

Table 3. Daily metabolic turnover of a human adult at light work.*

| | Input | Output |
|---|---|---|
| Water | 2200 gm | 2542 gm |
| Solids, Foods | 523 gm | - - |
| Solids, Waste | - - | 61 gm |
| Oxygen | 862 gm | - - |
| Carbon Dioxide | - - | 982 gm |
| TOTAL | 3585 gm | 3585 gm |

While man is doing light work and subsisting on the indicated diet, he is producing heat. Table 4 presents information about human heat production (53).

Table 4. Human heat production.

| | |
|---|---|
| Metabolic heat production, including latent heat of water vapor | 300-500 BTU/man/hr. |
| Average comfortable skin temperature | $92^{o}$F. |
| Average oral body temperature | $98.6^{o}$F. |
| Water vapor elimination, source of latent heat | 0.13-0.6 lb/man/hr. |
| Water vapor elimination during heavy work | 0.4-1.2 lb/man/hr. |

While it is possible to give a fairly complete account of the norms and ideals for the physical and physiological constraints which man places

* The man weighs 70 kg, uses 2830 kg-cal. Food is protein, 80 gm; carbohydrate, 270 gm; fat, 150 gm; minerals, 23 gm.

on an environment, it is more difficult to discuss the psycho-social constraints. While a great deal of work has been done to elucidate the effects of sensory deprivation, there is a paupicity of work which would throw light on the ideal psycho-social environment. We will briefly review what information is available and indicate pertinent variables to be investigated.

It is well known and well documented that isolation from society and his usual environment will eventually create behavioral disturbances in man. An excellent review of the data in this area, both experimental and case studies, is given by Wheaton (reference 99). The importance of this problem for the designers of man-machine systems which will operate in unusual environments is indicated by Bombard (reference 11), who states: "Examples confirmed the overwhelming importance of morale. Statistics show that 90 percent of survivors of shipwrecks die within three days--yet it takes longer to perish of hunger or thirst. When a man's ship goes down, his whole universe goes with him because he no longer has a deck under his feet, his courage and reason abandon him." Wheaton summarizes other case studies supporting Bombard's position.

An additional problem for the system designer is that crew members in isolated systems will suffer not only from stimulus deprivation, but from the constancy of what stimuli exist in their small confinement area. Man's needs are for a variety of stimulations, not for stimulation per se. Consequently, the repetitiveness of the same stimulus is irritating (the Chinese torture using the constant dripping water is brought to mind) and as a result crew members may find constant interaction with another crew member difficult to tolerate. This phenomena has been noted in some confinement studies (reference 42), and was called the Long Eye in the Antarctic (reference 81). The Long Eye was a condition in which for long periods of time interaction was terminated between an individual and the rest of the group, which termination might be initiated by either the group or the individual.

The study of isolation phenomena is a rich area of investigation which can be used to understand some of the basic facts about man and his nature, and how he lives with his kind. However, it must be recognized that such basic studies, while worthwhile and important, are not the concern of the system designer. Fortunately, we can greatly simplify this area for the purposes at hand by limiting our interests to whether or not man can perform assigned tasks so as to accomplish system requirements in isolated environments. The use of this criterion allows us to eliminate many problems in this area of investigation. For example, some of the most serious and rapid breakdowns in human behavior under isolation have occurred when visual stimulation was greatly reduced by placing half a ping-pong ball over the eyes. Such studies have been widely discussed, and are important for the study of primary processes in man, but are completely irrelevant for system design as man would not be useful in a man-machine system with ping-pong balls over his eyes. Similarly, an important area of concern and investigation is the problem of sex deprivation. However, it is apparent from the successful use of male submarine crews by many nations, the use of all male crews on long sea voyages for centuries, etc., that missions of up to a few years duration can be successfully accomplished without providing for normal sexual gratification. Consequently, this problem of sex deprivation can be ignored by the system designer, although it is in fact a problem that well may be of concern to others.

Analysis of the isolation problem suggests the rather simple hypothesis that man's psychological ability to perform his assigned tasks while confined to a restricted environment can be maintained as mission time increases by increasing crew size. The principle operating here is that the larger the crew the more the stimulus variation there is and the more of the culture that is present. That this relationship is correct seems apparent from the data on the failure of single individuals to maintain their psychological proficiency under isolation, whereas larger crews such as those on submarines do maintain proficiency. It can be noted that in these larger and successful crews, such as in submarines and in the Antarctic wintering-over missions, some individuals have had difficulties adjusting and that the success of the crews to meet the mission requirements could well have been due to some component redundancy which prevented individual failures from causing mission failures. Also, the more crew members there are, the greater the absolute space, even though space per man may not increase. Consequently, from a research standpoint there are some possible artifacts here. It is again important to note, however, that the problems of discomfort on the part of individuals, and basic theory and research problems are not the concern of the system designer. It is sufficient for the system designer to note that small crews over extended periods of time may break down psychologically and, therefore, produce mission failure whereas larger crews will not break down and the mission will be accomplished.

The information needed by the system designer is the size of crew needed to maintain psychological proficiency for given mission durations. A review of the available relevant data indicates a rapidly accelerating curve, with a single isolated man quickly losing his psychological proficiency, but with the period in which psychological proficiency is maintained rapidly increasing with additional crew members until a year or more is achieved with a group of fourteen. These data have been summarized in Table 5. The studies reviewed have been interpreted for their generalizability to the problem at hand. For example, one study of a one man crew (32) produced mission failure in two cases out of four after one and a half days, whereas another study (71) demonstrated no difficulties in ten men who were isolated individually for two days at a time. However, in the second study the men could see into the room as well as communicate at any time they wished on an intercom. Consequently, this second study seems less relevant than the first and it is, therefore, more prudent to consider one and a half days as the upper limit of confinement without psychological problems endangering mission accomplishment with a crew of one. This is the limit successfully approached on the Mercury Program by an exceptionally well motivated subject (40). In addition, only studies establishing maximum ranges for crew sizes are given. In some cases there were studies available indicating successful performance for shorter periods of time than the study cited showing successful performance for a longer period of time. A study of the data in Table 5 reveals rather clearly where additional research is needed, and where it is not needed, to determine the upper limit of successful performance by crew size. It is also apparent from the table that increasing crew size does increase length of time at which psychological capability can be maintained, and that excessive crew sizes are not necessary for this purpose.

Obviously, psychological variables other than crew size, e.g., work-rest cycle, are related to the maintenance of psychological capability. However, it is likely that crew size is the overriding factor, and the one on which the system designer needs help.

If the crew size is sufficient for the mission duration to hold the stimulus and cultural deprivation problems within required tolerances, the remaining psychological problems can probably be solved relatively easily, frequently by the crews themselves.

Table 5. Probable range of reliable crew performance when confined by size and mission duration.

| Crew Size | Days: Performance Maintained | Days: Performance Decrements | References* |
|---|---|---|---|
| 1 | 1.43 | 1.50 | 81, 32 |
| 2 | 7 | 30+ | 74, 73, 78, 42, 22 |
| 3 | | | |

* Only studies establishing maximum ranges with minimum crews are given. +performance did not deteriorate, but crew interaction difficulties developed that suggest performance maintenance doubtful under real isolation.

Table 5. (Cont.)

| Crew Size | Days | | References |
|---|---|---|---|
| | Performance Maintained | Performance Decrements | |
| 4 | | | |
| 5 | 5 | 15 | 82, 2 |
| 6 | | 15 | 2 |
| 7 | | | |
| 8 | | | |
| 9 | | | |
| 10 | 30 | | 2 |
| 11 | | | |
| 12 | | | |
| 13 | | | |
| 14 | 365 | | 81 |

Human tolerance of deviation from the ideal. - Deviation from the ideal or norm may, depending on the extent of the deviation, constitute a threat to man's ability to exist or to perform effectively in the given situation. This final section presents some of the known facts about man's ability to tolerate deviations from the ideal in certain selected aspects of the environment. This survey is limited to the physical and physiological constraints. Insufficient information is available on the psycho-social constraints to allow a similar survey.

Acceleration and Deceleration. - Figure 1 shows the duration of tolerance to acceleration for various bodily postures (12). The heavy line shows the time required to reach 18, 000 miles per hour for different values of g. When the direction of acceleration is vertical, a $13^{\circ}$ reclining position is better than an erect posture. When the acceleration is forward in the direction faced by the subject, the best position is to be inclined forward about $15^{\circ}$ from erect.

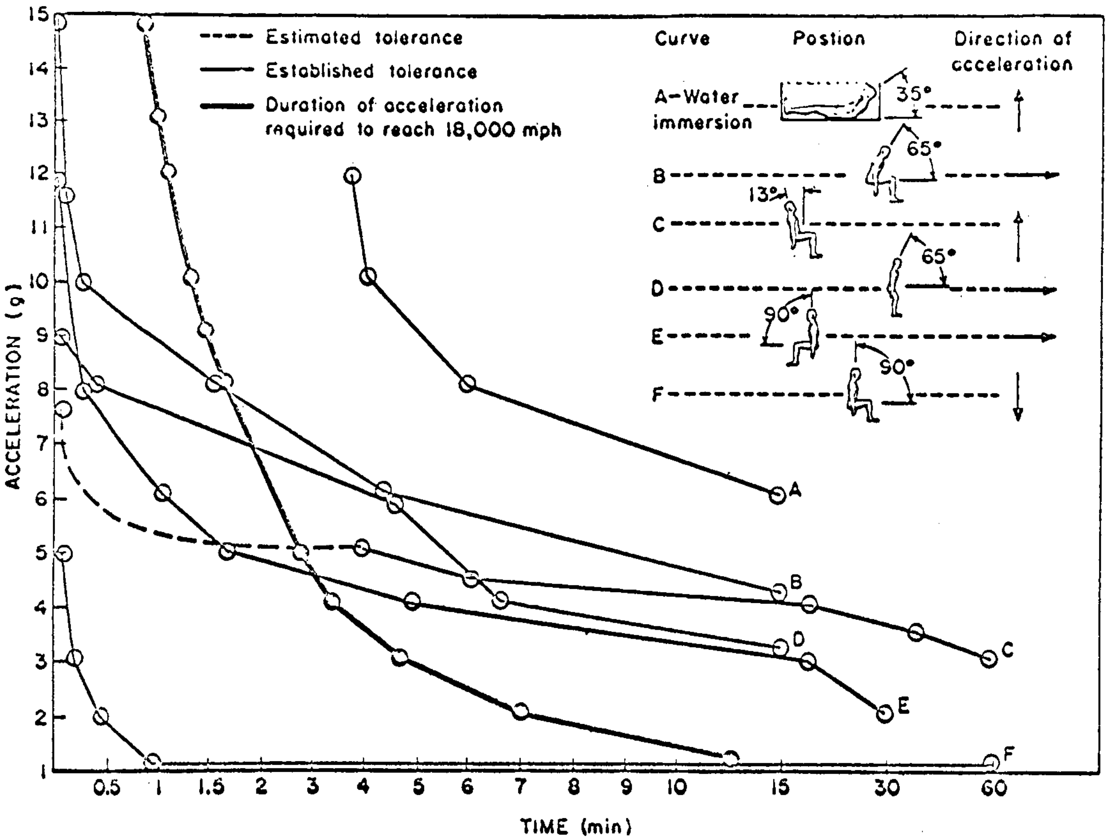



Figure 1. Duration of tolerance to acceleration for various bodily positions.

One of the problems in determining the effects of acceleration and deceleration on human tolerance limits is defining tolerance. Stoll has shown that greyout, blackout, confusion and unconsciousness all give different values of tolerances to maximum acceleration (92). See Figure 2.

Figure 3 shows the effects of rate of change, duration and magnitude of deceleration on the chimpanzee (93). The animals were seated forward and facing maximum restraint. In general, it has been concluded that decelerations of less than 40 g at a rate of onset lower than 600 g/sec., with a total exposure of less than 0.2 sec. can be readily tolerated, if

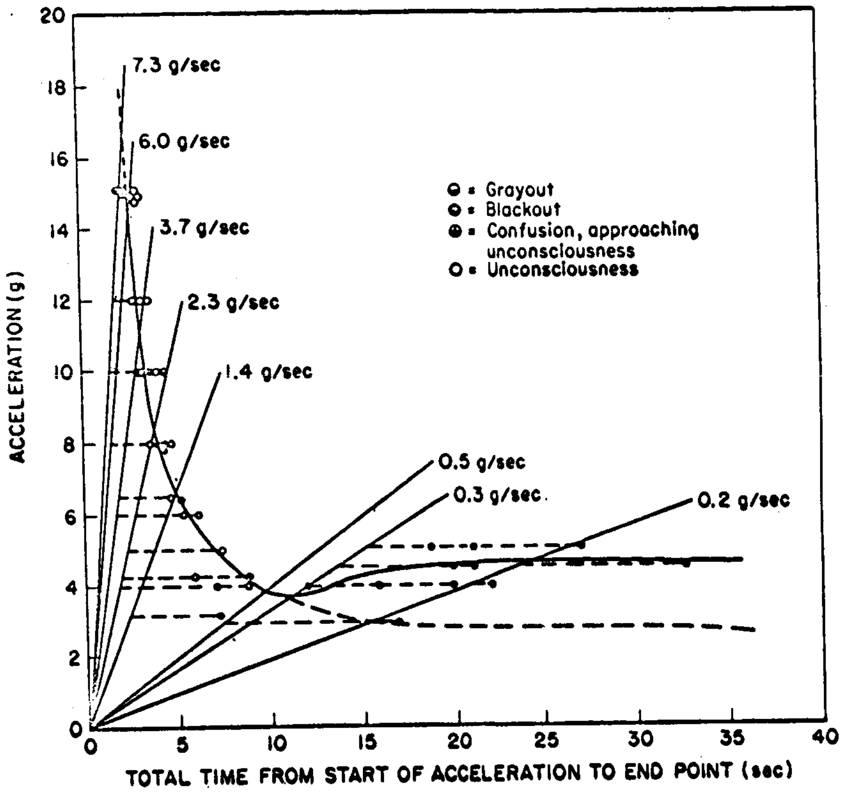



Figure 2. Acceleration tolerance curve relating dependent values of greyout, blackout, confusion and unconsciousness to maximum acceleration, exposure time and rate of application of g force.

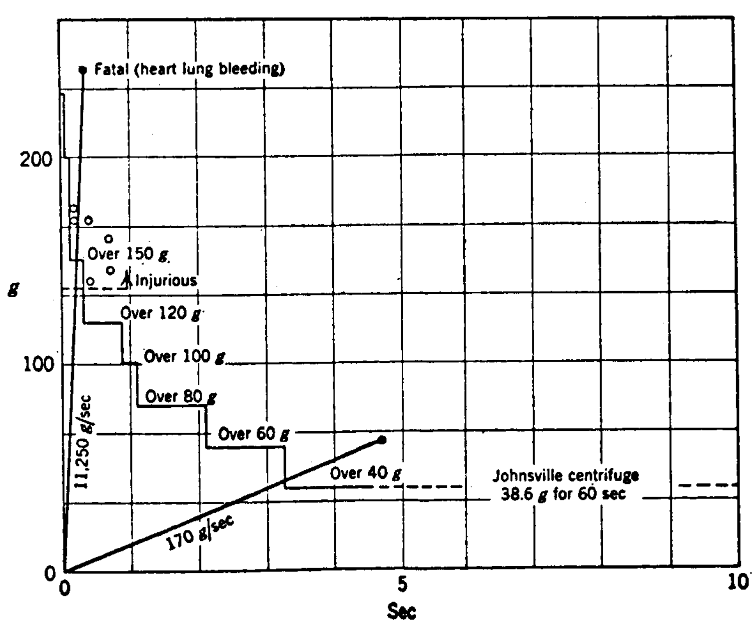
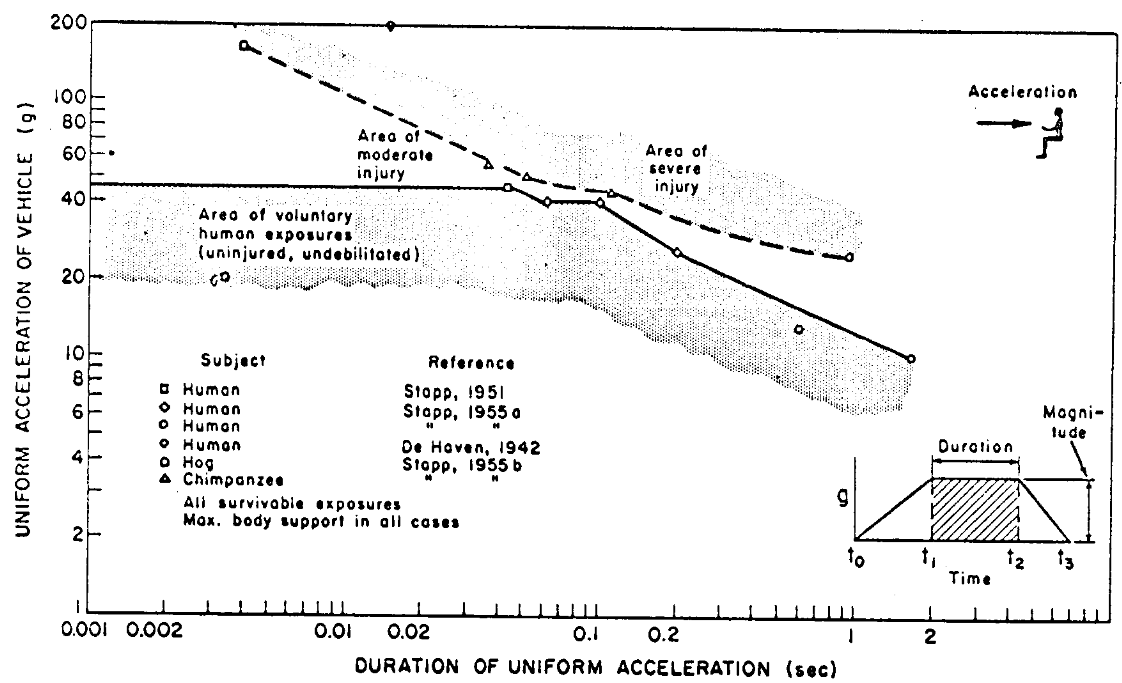
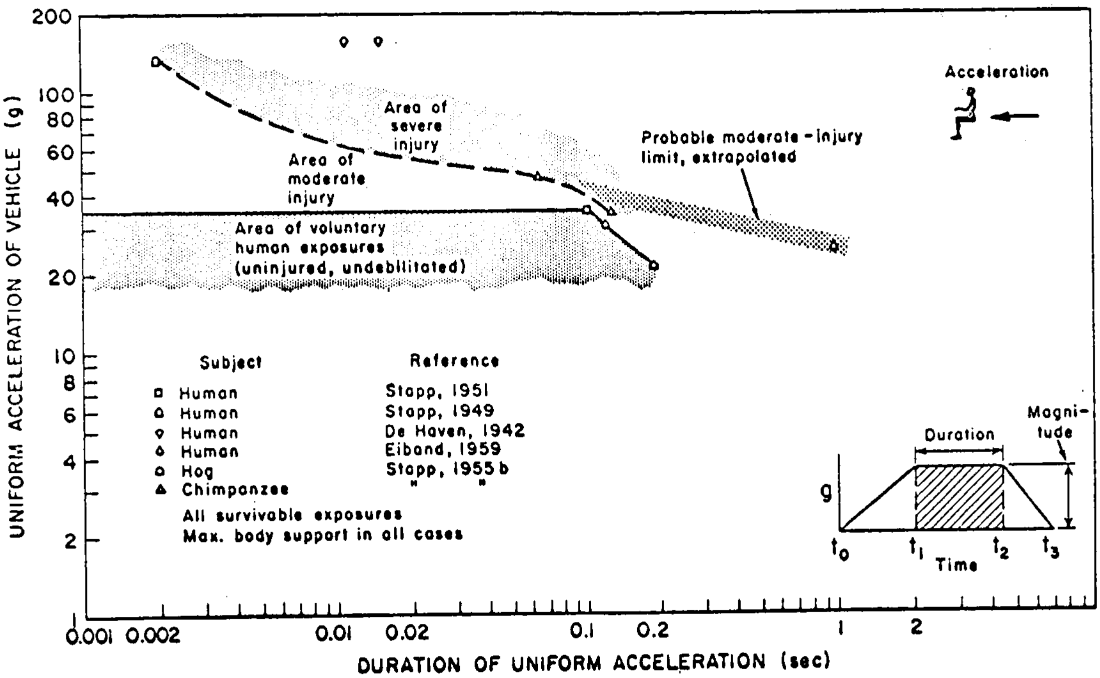



Figure 3. Effects of rate of change, duration and magnitude of deceleration.

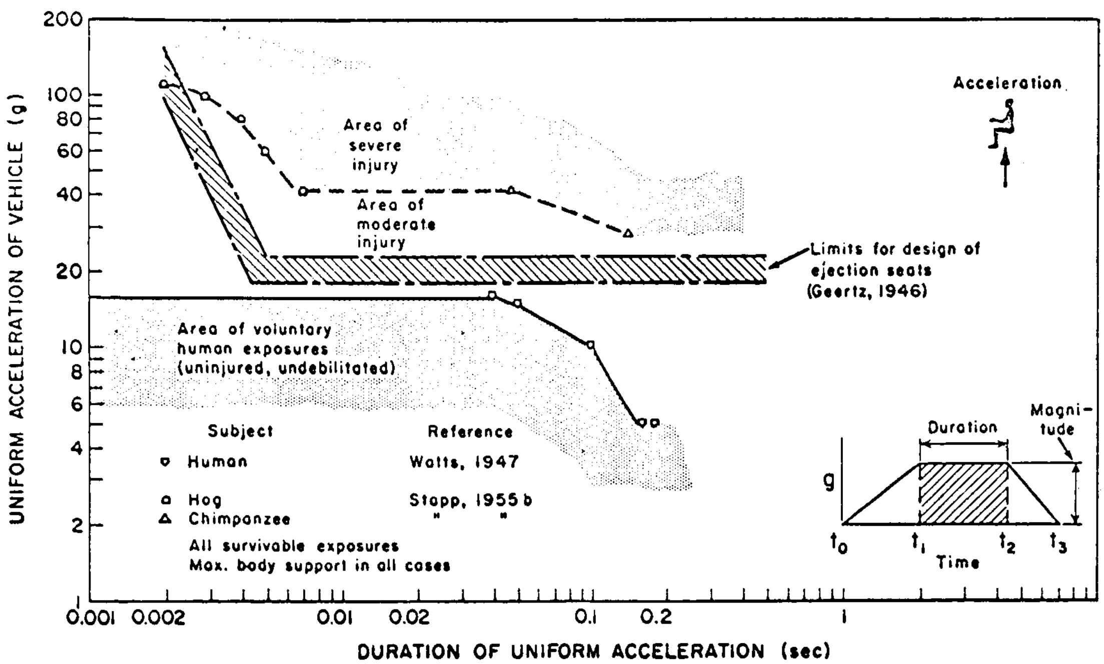
adequate protection is available. Tolerance of deceleration stress is greatest when the force of deceleration is transverse to the human body, which is true also for acceleration.

The effects of acceleration are dependent upon the orientation of the human body with respect to the g force (also true for deceleration). Figures 4, 5, 6 and 7 show the effects of direction of g forces relative to the human body orientation and magnitude and duration of uniform acceleration (26).

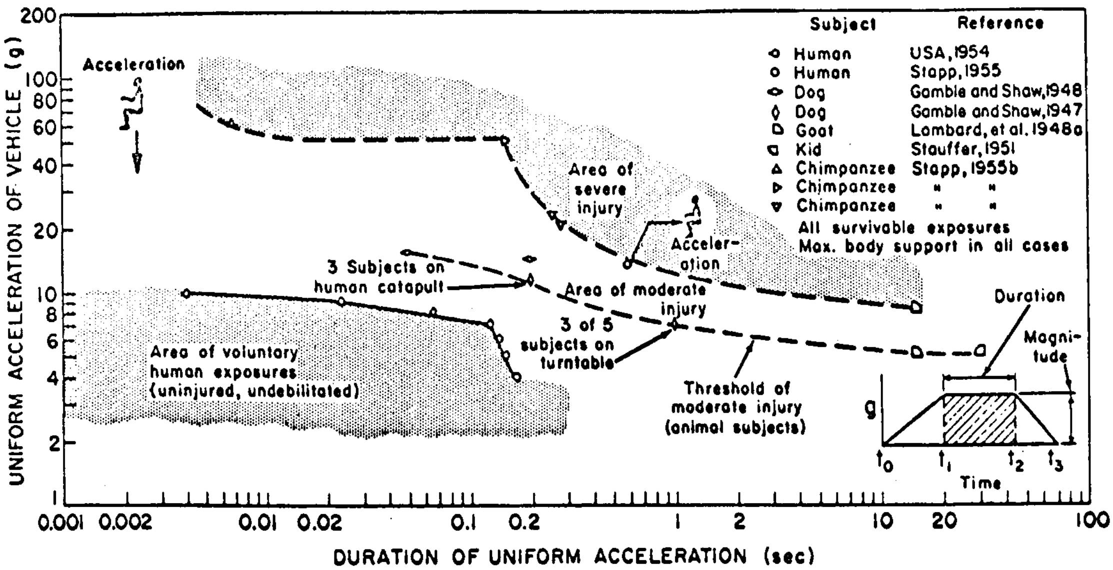




Acceleration
Area of severe injury
Area of moderate injury
Probable moderate-injury limit, extrapolated
Area of voluntary human exposures (uninjured, undebilitated)
Subject
Reference
Human
Stapp, 1951
Human
Stapp, 1949
Human
De Haven, 1942
Human
Eiband, 1959
Hog
Stapp, 1955 b
Chimpanzee
All survivable exposures
Max. body support in all cases
Duration
Magnitude
g
Time
UNIFORM ACCELERATION OF VEHICLE (g)
DURATION OF UNIFORM ACCELERATION (sec)

Acceleration
Area of severe injury
Area of moderate injury
Limits for design of ejection seats (Geertz, 1946)
Area of voluntary human exposures (uninjured, undebilitated)
Subject
Reference
Human
Watts, 1947
Hog
Stapp, 1955 b
Chimpanzee
All survivable exposures
Max. body support in all cases
Duration
Magnitude
g
Time
UNIFORM ACCELERATION OF VEHICLE (g)
DURATION OF UNIFORM ACCELERATION (sec)




Figures 4-7. Limits of human tolerance to abrupt acceleration.

Figure 8 shows the effects of acceleration on the accuracy of dial reading for different levels of luminance (100). As luminance increases the percent of error decreases, until at 42 milli-lamberts there is no longer an effect due to acceleration (4 g maximum).

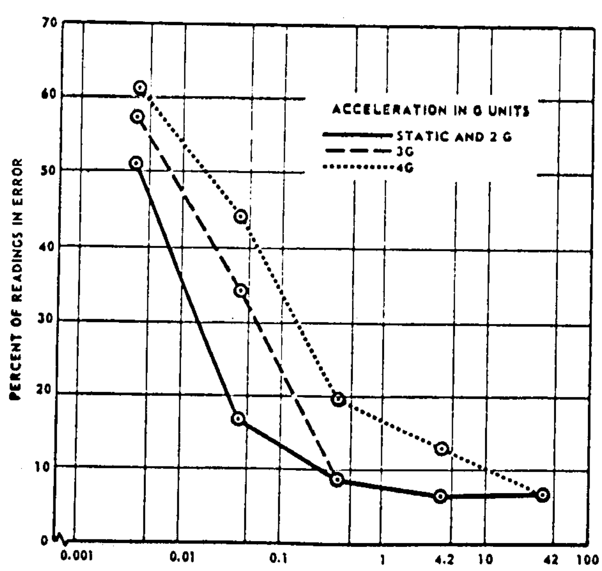



Figure 8. Effect of acceleration on dial reading accuracy as a function of luminance.

Acceleration, to 4 g, has the effect of increasing both foveal and percepteral thresholds for vision, as is shown in Figures 9 and 10 (101). The targets were achromatic circles projected on a larger achromatic background.

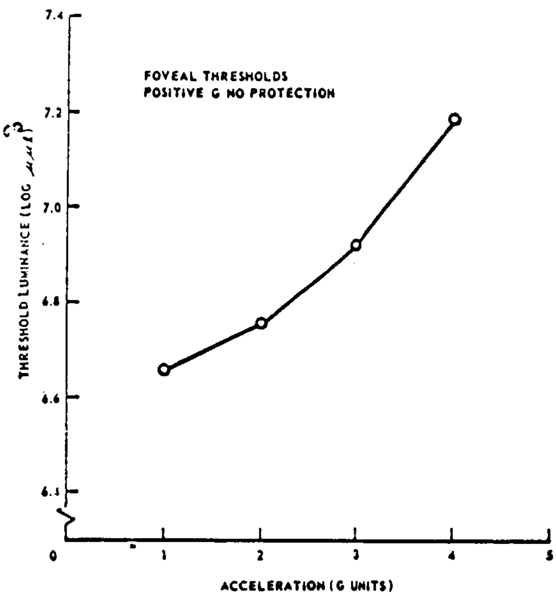



Figure 9. Foveal threshold as a function of acceleration.

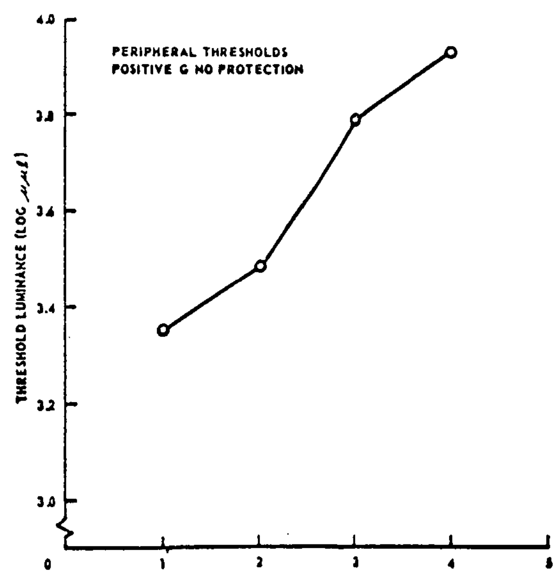



Figure 10. Peripheral threshold as a function of acceleration.

Noise and vibration. - High energy acoustic noise can produce a variety of symptoms in man, including nausea, disorientation, deafness, injury to internal organs (<100-200 cps) and death. However, man is most frequently hurt by vibratory energy in the range 0.5-10 cps, since he absorbs most of the energy of vibrations in this range. Figure 11 shows human vibration tolerances as a function of acceleration and frequency in cycles per second, from 1 to 16 cps (63). The curve of Figure 11 is attenuated by reluctance on the part of subjects to continue due to the development of discomfort and pain in the head, the chest, abdomen and testicles. Pain symptoms were often accompanied by dyspnea (labored respiration) and anxiety.

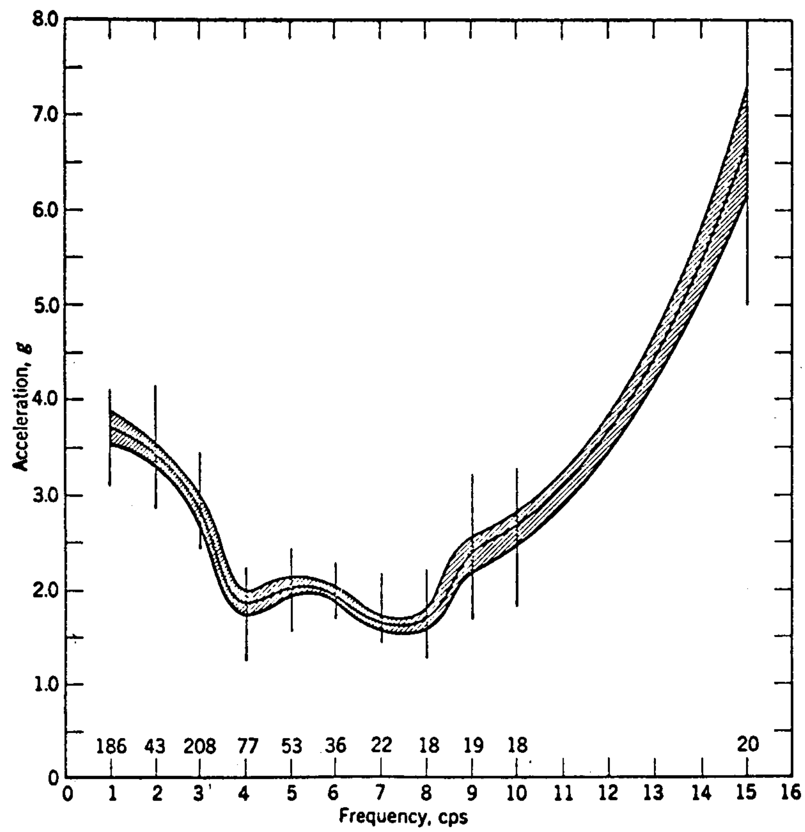



Figure 11. Human tolerance to low frequency vibrations.

The effects of noise are related to the duration of that noise. Figure 12 shows the available noise exposure per day.*

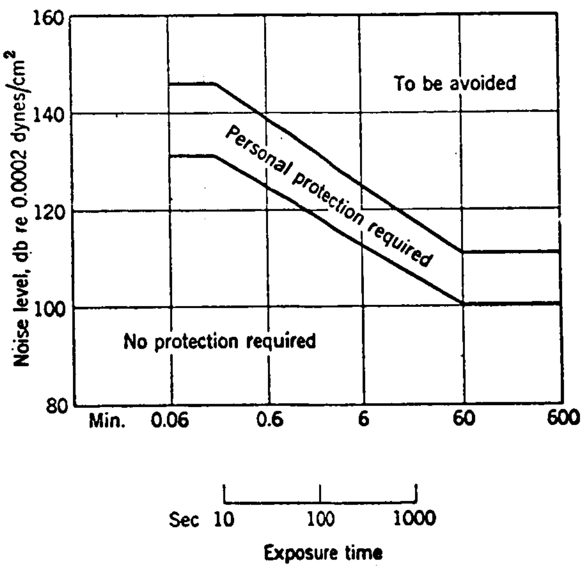



Figure 12. Allowable noise exposure per day.

Similarly, Table 6 shows permissible values of noise intensity and duration, with and without ear plugs (65). It will be noted that of the two sets of estimates, Figure 12 is more conservative.

Table 6. Permissible values for noise intensity and duration.

| Sound Level, db in 0.0002 dynes/cm² | Maximum Allowable Exposure Time |
|---|---|
| **With no ear protection** | |
| 108 | 1 hr |
| 120 | 5 min |
| 130 | 30 sec |
| 135 | 10 sec or less |
| **With ear plugs** | |
| 112 | 8 hr |
| 120 | 1 hr |
| 132 | 5 min |
| 142 | 30 sec |
| 147 | 10 sec |

*Based on Air Force experience. (NASA Memo 3-5-59L. Also Tempo Report, Supporting man in space: 1970-1975. General Electric)

Table 7 shows the human body response to vibration stress (76).

Table 7. Human body vibration response to stress.

| Frequency | Amplitude | Effective *g* | Response | Critical Time |
|---|---|---|---|---|
| 10 cps | $\frac{1}{3}$ in. | 2 *g* | Intense precardial pain | 3 min |
| 25 cps | $\frac{1}{3}$ in. | 4–6 *g* | Bowel and bladder damage | 8 min |
| 40 cps | $\frac{1}{3}$ in. | 4 *g* | Eyeball and brain damage | 5 min |

Table 8 summarizes the effects of noise, as compared with quiet on human performance (25). Table 8 shows that noise may not necessarily be detrimental to human performance, although, in general it is.

Table 8. Effects of exposure to noise as compared with quiet on human performance

| Type of performance | Noise level (db) | Noise duration | Quiet level (db) | Effect of noise |
|---|---|---|---|---|
| Addition problems | 50 | Continuous | Not given | No difference in number of correct solutions. Considerable increase in energy expenditure under noise as compared to quiet, especially during first few days. |
| Continuous tracking | 120 | Intermittent and random | " " | No effect , |
| | 120 | 12 × 2 min. in 4 hours | " " | Performance improved |
| | 130 | 3 min. at middle and end of 4 hours | " " | Performance improved |
| Stereoscopic ranging | 120 | 3 minutes | " " | No effect |
| Inserting pegs in pegboard | high | Intermittent clicks and complex noise | " " | Initial performance slowed but over-all performance showed no difference |
| Tracking requiring hand, foot, and eye coordination | 115 | continuous | 90 | Reactions in noise 5.4% slower |
| Card sorting | 115 | continuous | 90 | No effect |
| Marksmankship | 115 | continuous | 90 | No effect |
| Joystick pursuit tracking | 115 | continuous | 90 | No effect |
| Hand or foot key-pressing | 115 | continuous | 90 | No effect |
| Key pressing to translate letters to numbers | 120 | 10 minutes | not given | Time required initially longer; greater tension in noise |
| Monitoring clock for erratic hand movements | 114 | last 1½ hours of 2-hour trial | 83 | Significantly poorer in last ½ hour |
| Conversation | 0–60 | continuous | — | Normal |
| | 60–80 | " | — | Raised voice |
| | 80–100 | " | — | Very difficult |
| | 100–115 | " | — | Shouting |
| | < 115 | " | — | Impossible |
| Comfort level in aircraft | 0–60 | Continuous | — | Quiet and very comfortable |
| | 60–80 | " | — | Comfortable |
| | 80–90 | " | — | Acceptable |
| | 90–100 | " | — | Noisy |
| | 100–115 | " | — | Very noisy and disagreeable |
| | 115–125 | " | — | Uncomfortable |
| | < 125 | " | — | Painful |

(After Eckenrode and Abbot, 1959)

Figure 13 shows the increase in errors for reading accuracy as a function of vibration amplitude for seven different levels of brightness (Ft.-L). There is no decrement due to vibration if brightness is great enough (5.400 Ft.-L or greater). For brightness values of 0.21 to 1.00 Ft.-L, the decrement begins with subtended visual angles of about 4 minutes (23).

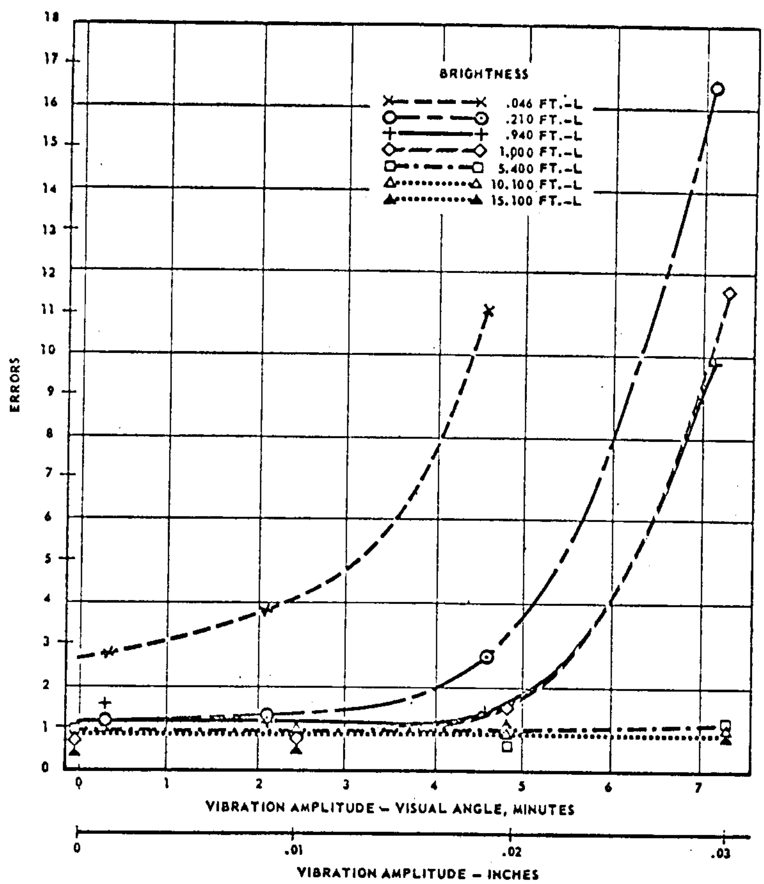



Figure 13. Effect of vibration amplitude on reading accuracy for various luminances.

Figure 14 shows the human reaction to sinusoidal whole body vibration (72). The maximum effect, as well as the maximum variability of response, is 16-17 cps.

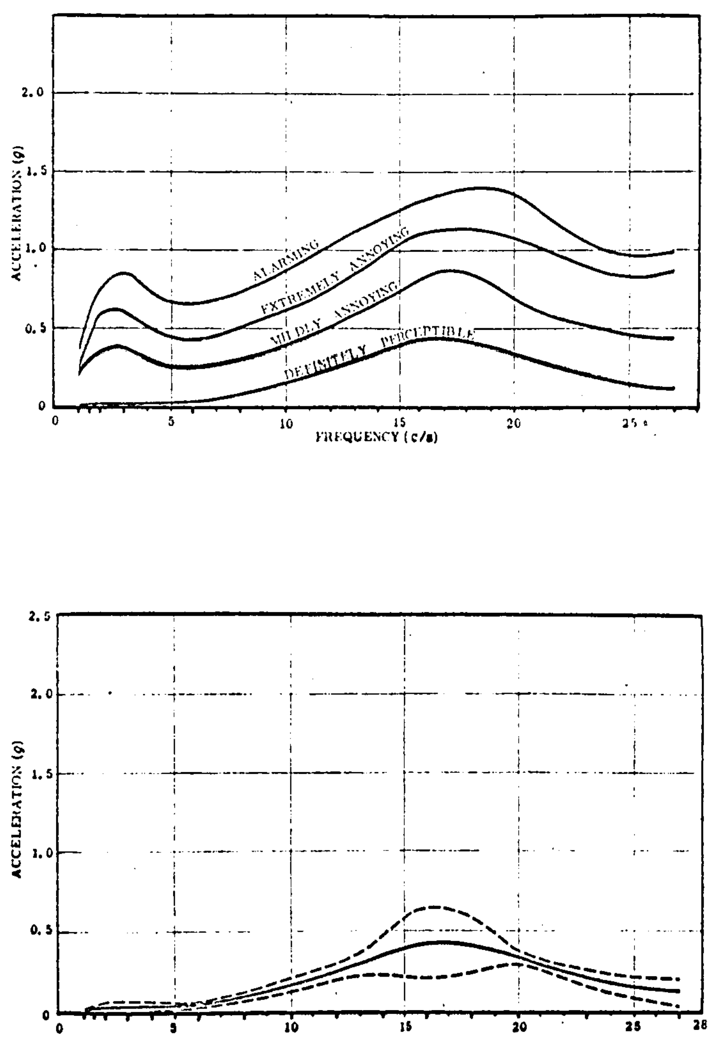



Figure 14. Human reaction to sinusoidal whole-body vibration.

Temperature.- The effects of temperature are in part determined by the kind of activity in which man is engaged. Figure 15 shows that his performance requiring only light physical activity is most susceptible to heat stress (10).

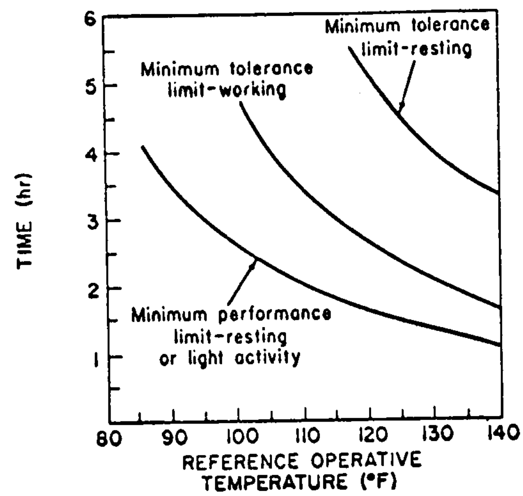



Figure 15. Human performance susceptibility to heat stress.

Figure 16 shows human temperature tolerance with anti-exposure suit and ventilation garment (76). It is interesting that performance is impaired much before the temperature becomes intolerable.

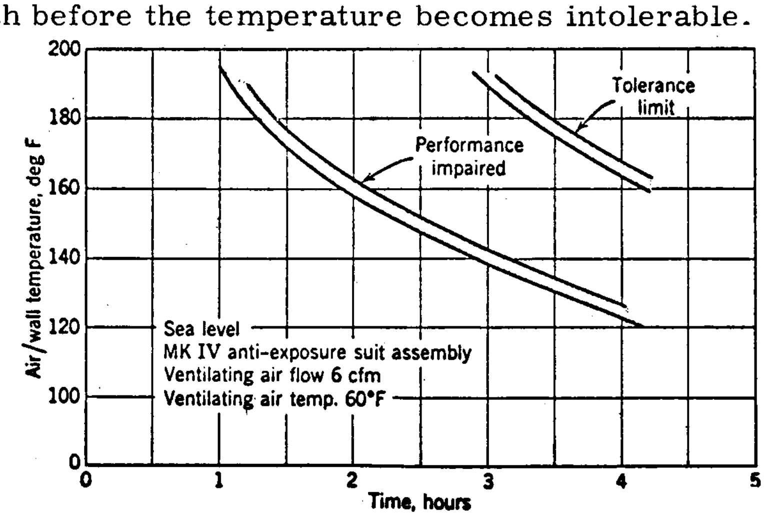



Figure 16. Human temperature tolerance with anti-exposure suit and ventilation garment.

Figure 17 shows the temperature-time relationship for safe heat and cold exposures (15). Figure 17 considers the effects of humidity on safe exposure.

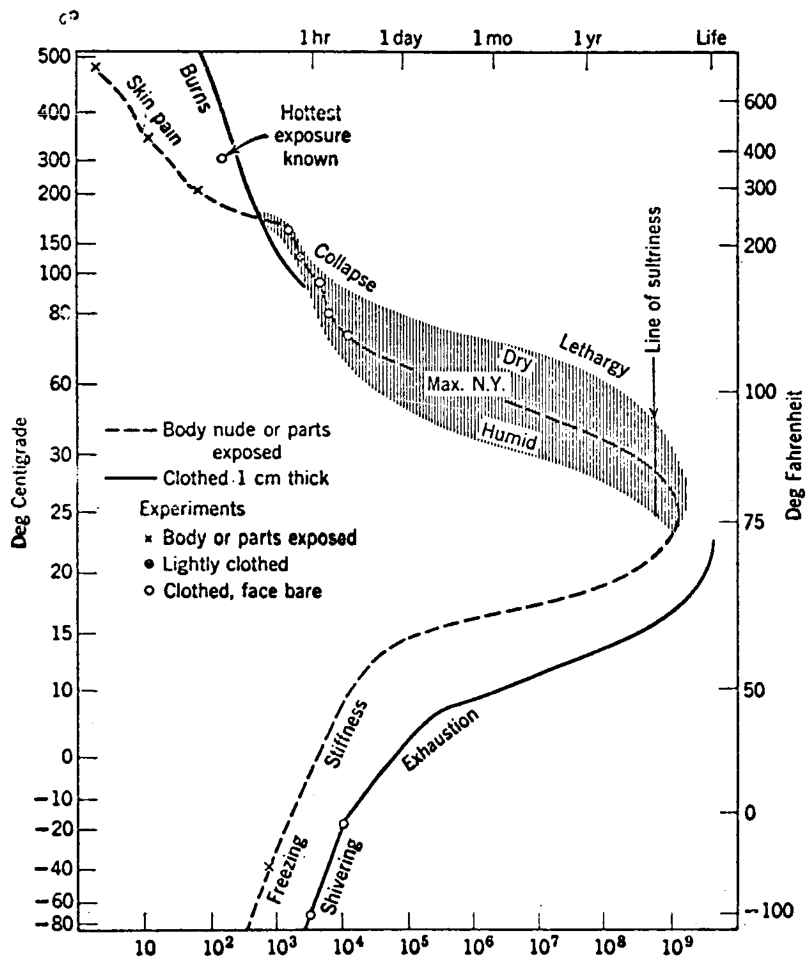



Figure 17. Temperature-time relationships. Safe heat and cold exposure times for healthy, normal men at rest with body wholly or partly exposed.

Figure 18 shows the predicted total insulation required for prolonged comfort for various activities performed in the shade as a function of ambient temperature (9).

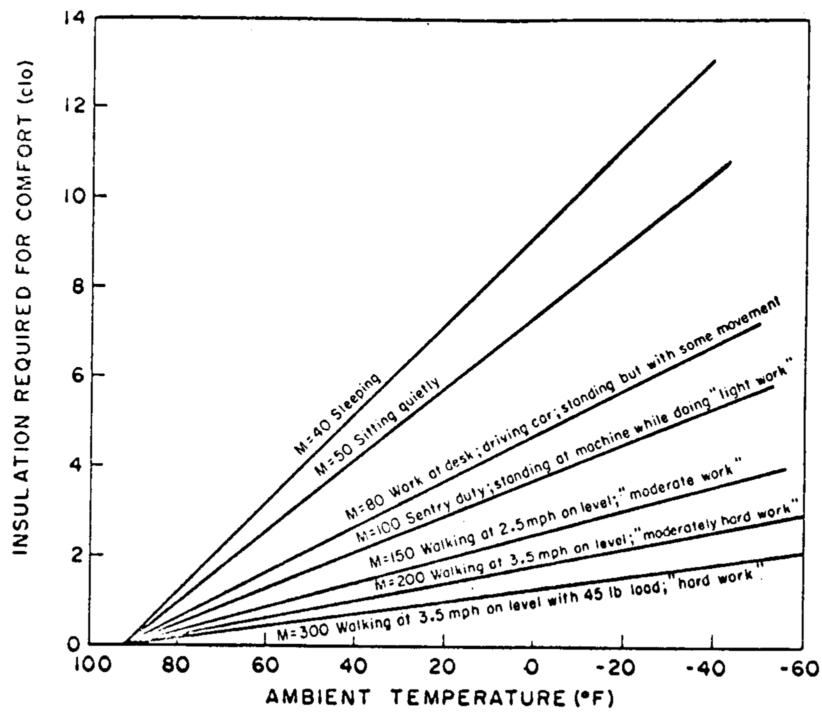



Figure 18. Prediction of total insulation required for prolonged comfort at various activities in the shade as a function of ambient temperature.

Table 9 shows the critical temperature at which impairment may be demonstrated for various types of activities (25).

Table 9. The critical effective temperatures at which impairment may be demonstrated.

| Name and type of test | Investigator | Temperature (°F) | |
|---|---|---|---|
| | | Max. at which performance remains normal | Demonstrable impairment |
| Typewriter code (scrambled letters) | Viteles | 80 | 87 |
| Morse code reception | Mackworth | 87.5 | 92[a] |
| Locations (spatial relations code) | Viteles | 80 | 87 |
| Block coding (problem solving) | Mackworth | 83 | 87.5[a] |
| Mental multiplication (problems) | Viteles | 80 | 87 |
| Number checking (error detection) | Viteles | 80 | 87[a] |
| Visual attention (clock test) | Mackworth | 79 | 87.5[a] |
| Pursuit (visual maze) | Viteles | 80 | 87 |
| Reaction time (simple response) | Forlano | 93[b,c] | — |
| Discrimeter (complex response) | Viteles | 80 | 87 |
| Lathe (hand coordination) | Viteles | 80 | 87[a] |
| Pursuitmeter | Mackworth | 87.5 | 92[a] |
| Motor coordination | Weiner | 64.5[c] | 91[a] |
| Ergograph (weight pulling) | Mackworth | 81[d] | 85.3[a,d] |
| Bicycle ergometer (heavy work) | Liberson | 64.5[c] | 91.5[c] |
| Weight lifting (heavy work) | N. Y. Ventil. Comm. | 64.5[c] | 70[c] |

[a] Deterioration statistically significant.
[b] Provided wet bulb does not exceed 86°F.
[c] Effective temperature estimated from data in report.
[d] Midpoint of a range of conditions.

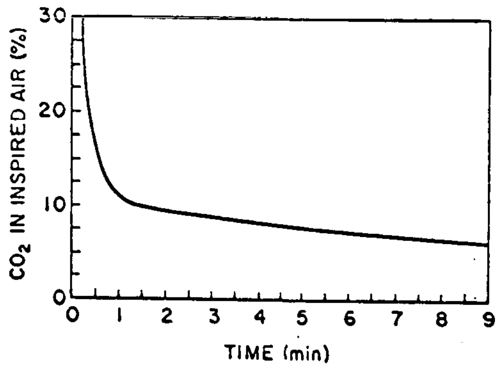
(After Eckenrode and Abbot, 1959)

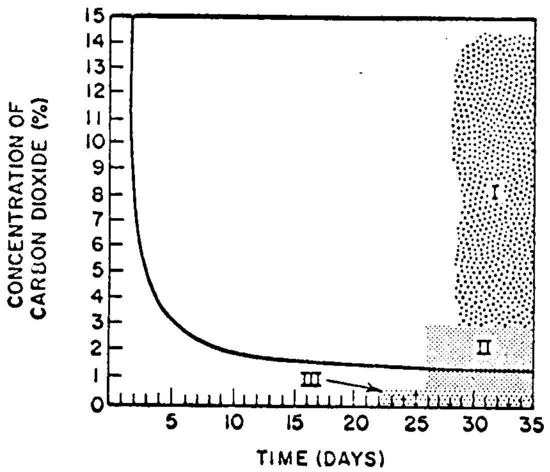
Tolerance to gases and vapors. - Table 10 lists human tolerances to various gases and vapors, in concentration of substance in parts per million (46). The human tolerance to ozone is an order of magnitude less than that of any other substance.

Table 10. Human tolerances to various gases and vapors: concentrations in parts per million.

| Substance | Maximum Allowable Concentration |
|---|---|
| Ammonia | 100 |
| Amyl acetate | 200 |
| Benzene | 100 |
| Butyl acetate | 200 |
| Carbon dioxide | 5,000 |
| Carbon disulfide | 20 |
| Carbon monoxide | 100 |
| Carbon tetrachloride | 50 |
| Chlorine | 1 |
| Dichloroethyl ether | 15 |
| Dichlorodifluoromethane | 100,000 |
| Ether | 400 |
| Ethyl acetate | 400 |
| Ethyl alcohol | 1,000 |
| Ethylene dichloride | 100 |
| Formaldehyde | 10 |
| Gasoline | 500 |
| Hydrogen chloride | 10 |
| Hydrogen cyanide | 20 |
| Hydrogen fluoride | 3 |
| Hydrogen sulfide | 20 |
| Methane | 10,000 |
| Methyl bromide | 20 |
| Methyl chloride | 100 |
| Nitric oxide | 25 |
| Nitrogen dioxide | 25 |
| Ozone | 0.05 |
| Phenol | 5 |
| Phosgene | 1 |
| Styrene | 400 |
| Sulfur dioxide | 10 |
| Toluene | 200 |
| Trichloroethylene | 200 |

Figure 19 shows the time to unconsciousness as a function of the amount of $CO_2$ in inspired air (83). Figure 20 shows the length of time required to adapt to chronic $CO_2$ toxicity for three limits of activity (83).




Figures 19 & 20. Time-concentration curve for adaptation to carbon dioxide. (Three levels for chronic $CO_2$ toxicity are: (I) 3% $CO_2$ and above; (II) 1.5-3.0% $CO_2$; (III) 0-1.5% $CO_2$)

Since carbon monoxide reduces the amount of oxygen in the blood, it is convenient to express carbon monoxide in terms of physiological altitude. Figure 21 shows physiological altitude as a function of percentage of carbon monoxide in the hemoglobin (23).

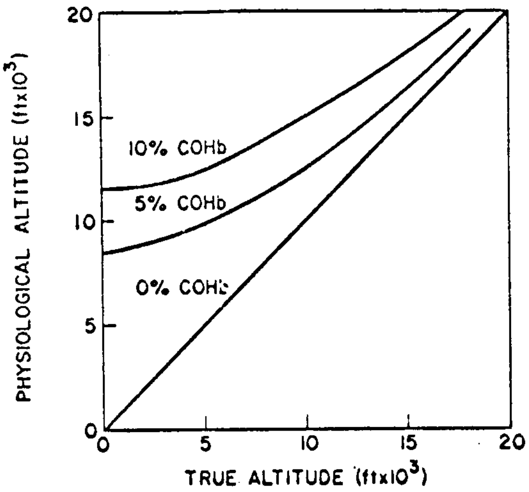



Figure 21. Physiological altitude as a function of percentage of carbon monoxide in the hemoglobin.

Radiation.- Table 11 shows the maximum permissible radiation dosages and some typical exposures, in roentgens (68).

Table 11. Maximum permissible radiation dosages and typical exposure levels, in roentgens.

| Item | Amount |
|---|---|
| Permissible Exposures | |
| Maximum permissible dosages | 0.3 r/quarter[a]<br>12.0 r/yr |
| Maximum permissible emergency exposure | 25 r |
| Typical Exposures | |
| Normal radiation level, sea level | 0.001 r/day |
| Undisturbed interplanetary space, cosmic rays | 5–12 r/yr |
| Heart of inner belt, protons | 24 r/hr |
| Heart of outer belt, soft X-rays | ~200 r/hr |
| Solar proton event, protons | 10–$10^3$ r/hr |
| Total exposure | 200–400 r |

From Newell and Naugle

[a] Limit prescribed for radiation workers. Under this limit the yearly maximum would be 1.2 r.

Figure 22 shows the acute effects of gamma radiation in non-human primates (36).

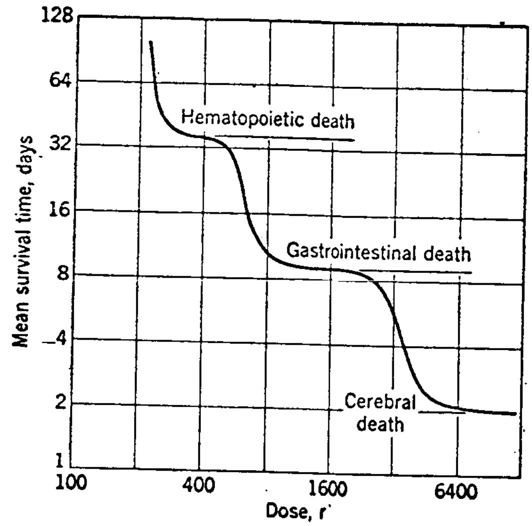



Figure 22. Acute effects of gamma radiation in primates. Dose survival time predicted for man.

Coriolis effect. - The coriolis effect is a feeling of nausea and discomfort which results when a subject moves his head at right angles to an axis of rotation. Figure 23 illustrates some of the situations in which a person might experience this effect (58).

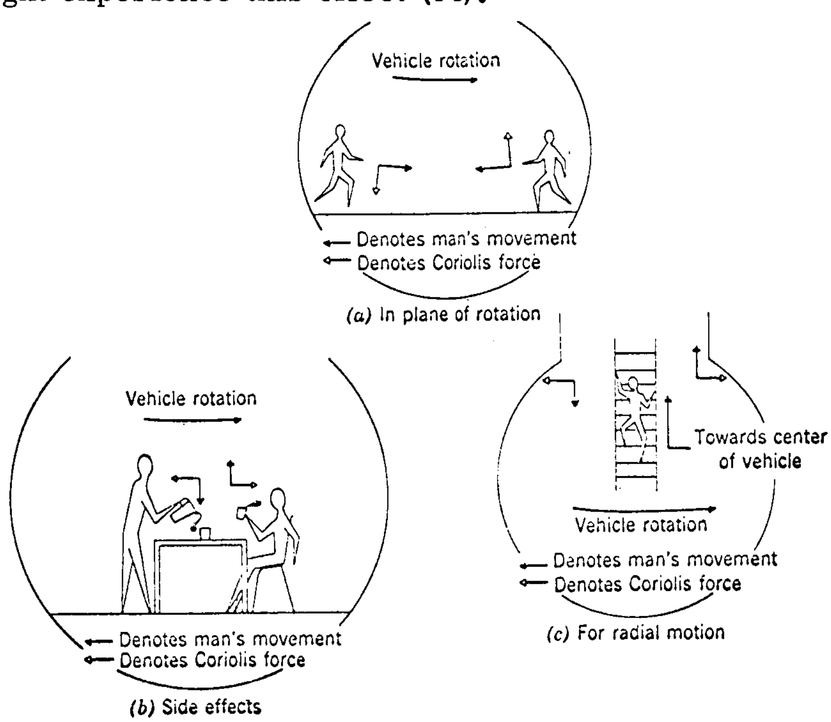



Figure 23. Coriolis effects

Weightlessness.- It has been predicted many times that weightlessness would be a problem in space travel. To date no physiological or physical problems have been associated with weightlessness. However, it is established that there will be problems of motion in a weightless condition. In fact, it has been estimated that man might best revert to swimming as a means of movement under conditions of weightlessness (39). This means, that for prolonged space flight man may find that he has to learn an entirely new set of skills and that he may have to be aided, or be tied down,to:

1. move from one place to another;
2. apply a force with a wrench;
3. perform exercises;
4. engage in recreational activities.

It has been suggested that for prolonged space flight, it would be possible to provide an artificial gravity of 0.5-0.8 g, to assist man in adapting to the weightlessness condition.

## Human Capability

The number of senses which man possesses is, to some extent, a function of the authority to whom one appeals, i.e., the system of classification used. Table 12 is a survey of man's senses and the physical energies to which they are responsive (67). The human is sensitive, to some degree, to a wide variety of physical energies. To our knowledge man is the only system component which is capable of response to such a wide variety of input energies.

Table 13 presents the range of stimulus intensities to which man's senses are responsive (67).

Table 14 presents the range of frequencies which are detectable and the relative and absolute frequency discrimination abilities of the eye, the

Table 12. Survey of man's senses and the physical energies which stimulate them.

| *Sensation* | *Sense organ* | *Stimulation* | *Origin* |
|---|---|---|---|
| Sight | Eye | Some electromagnetic waves | External |
| Hearing | Ear | Some amplitude and frequency variations of pressure in surrounding media | External |
| Rotation | Semicircular ear canals | Change of fluid pressures in inner ear | Internal |
| | Muscle receptors | Muscle stretching | Internal |
| Falling and rectilinear movement | Semicircular ear canals | Position changes of small, bony bodies in inner ear | Internal |
| Taste | Specialized cells in tongue and mouth | Chemical substances dissolvable in saliva | External on contact |
| Smell | Specialized cells in mucous membrane at top of nasal cavity | Vaporized chemical substances | External |
| Touch | Skin | Surface deformation | On contact |
| Pressure | Skin and underlying tissue | Surface deformation | On contact |
| Temperature | Skin and underlying tissue | Temperature changes of surrounding media or objects, friction, and some chemicals | External on contact |
| Pain | Unknown, but thought to be free nerve endings | Intense pressure, heat, cold, shock, and some chemicals | External on contact |
| Position and movement (kinesthesis) | Muscle nerve endings | Muscle stretching | Internal |
| | Tendon nerve endings | Muscle contraction | Internal |
| | Joints | Unknown | Internal |
| Mechanical vibration | No specific organ | Amplitude and frequency variations of pressure | External on contact |

*Mowbray and Gebhard, 1958.

Table 13. Comparison of the stimulus intensity ranges of the senses.

| Sensation | Range of stimulation intensity | |
|---|---|---|
| | Smallest detectable | Largest practical |
| Sight | 2.2–5.7 $\times 10^{-10}$ ergs | $\sim 10^9 \times$ threshold intensity |
| Hearing | $1 \times 10^{-9}$ erg/cm$^2$ | $\sim 10^{14} \times$ threshold intensity |
| Mechanical vibration | 0.00025 mm average amplitude at fingertip | $\sim$40 db above threshold |
| *Touch (pressure) | 0.026 erg at ball of thumb | No data available |
| Smell | $2 \times 10^{-7}$ mg/m$^3$ of vanillin | No data available |
| Taste | $4 \times 10^{-7}$ molar concentration of quinine sulfate | No data available |
| Temperature | 0.00015 gm-cal/cm$^2$/sec for 3-sec exposure of 200 cm$^2$ of skin | 0.218 gm-cal/cm$^3$/sec for 3-sec exposure of 200 cm$^2$ of skin |
| Position and movement | 0.2–0.7 deg at 10-deg/min for joint movements | No data available |
| Angular acceleration | 0.12 deg/sec$^2$ for oculogyral illusion | Positive-g forces of 5–8g lasting 1 sec or more<br>Negative-g forces of 3–4.5g |
| Linear acceleration | 0.08g for deceleration | Same limitations as for angular acceleration for forces acting in direction of long axis of body |

* Mowbray and Gebhard, 1958.

ear and the tactile sense (67). The contrast between the relative and the absolute frequency discrimination ability of the human senses is remarkable.

Table 15 presents the intensity discrimination abilities for sight, hearing and the tactile sense (67). Again, note the differences between relative and absolute discrimination ability. The values for absolute discrimination compare very favorably with those obtained for other judgments, e.g., the number of different weights in a series.

Table 14. Comparison of the frequency-detectability range and frequency-discrimination abilities of some of the senses.

| Stimulant or sensation | Frequency-detectability range | | Frequency-discrimination ability | |
|---|---|---|---|---|
| | Lowest | Highest | Relative | Absolute |
| Color (hue) | 300 mμ | 1,050 mμ at extremely high intensities | ~128 discriminable hues at medium intensities | 12 or 13 discriminable hues |
| Interrupted white light | One interruption | ~50 interruptions/sec at moderate intensities and duty cycle of 0.5 | 375 discriminable interruption rates between 1–45 interruptions/sec at moderate intensities and duty cycle of 0.5 | 5 or 6 discriminable interruption rates |
| Pure tones | 20 cps | 20,000 cps | 1,800 discriminable tone differences between 20 cps and 20,000 cps at 60 db loudness | 4 or 5 discriminable tones |
| Interrupted white noise | One interruption | ~2,000 interruptions/sec at moderate intensities and duty cycle of 0.5 | 460 discriminable interruption rates between 1–45 interruptions/sec at moderate intensities and duty cycle of 0.5 | Unknown |
| Mechanical vibration | 1 cps | 10,000 cps at high intensities | 180 discriminable frequency differences between 1 and 320 cps | Unknown |

* Mowbray and Gebhard, 1958.

Table 15. Comparison of the discrimination abilities of some of the senses.

| Sensation | Discrimination ability | |
|---|---|---|
| | Relative | Absolute |
| Sight | ~570 discriminable intensity differences with white light | 3–5 discriminable intensities in white light of 0.1–50 mL |
| Hearing | ~325 discriminable intensity differences at 2,000 cps | ~3–5 discriminable intensities with pure tones |
| Mechanical vibration | 15 discriminable amplitudes in chest region using broad contact vibrator with 0.05–0.5 mm amplitude limits | 3–5 discriminable amplitudes |

* Mowbray and Gebhard, 1958.

Table 16. Characteristics of the senses.

| Parameter | Vision | Audition | Touch | Taste and Smell | Vestibular |
|---|---|---|---|---|---|
| Sufficient stimulus | Light-radiated electromagnetic energy in the visible spectrum | Sound-vibratory energy, usually airborne | Tissue displacement by physical means | Particles of matter in solution (liquid or aerosol). | Accelerative forces |
| Spectral range | Wavelengths from 400 to 700 mu. (violet to red) | 20 cps. to 20,000 cps. | >0 to <400 pulses per second | Taste—salt, sweet, sour, bitter. Smell—fragrant, acid, burnt, and caprylic | Linear and rotational accelerations. |
| Spectral resolution | 120 to 160 steps in wavelength (hue) varying from 1 to 20 mu. | ~3 cps. (20 to 1000 cps.) 0.3 percent (above 1000 cps.) | $\frac{\Delta pps}{pps} \cong 0.10$ | — | — |
| Dynamic range | ~90 db. (useful range) for rods = 0.00001 mL to 0.004 mL; cones = 0.004 mL to 10,000 mL | ~140 db. 0 db = 0.0002 dyne/cm² | ~30 db. .01 mm to 10 mm | Taste ≅ 50 db $3 \times 10^{-5}$ to 3% concentration quinine sulphate. Smell = 100 db. | Absolute threshold ≅ 0.2°/sec/sec |
| Amplitude resolution $\frac{\Delta I}{I}$ | contrast = $\frac{\Delta I}{I} = .015$ | .5 db (1000 cps. at 20 db or above.) | ~.15 | Taste ≅ .20 Smell: .10 to 50 | ~.10 change in acceleration |
| Acuity | 1° of visual angle | Temporal acuity (clicks) ≅ 0.001 sec. | Two point acuity = 0.1 mm (tongue) to 50 mm (back) | — | — |
| Response rate for successive stimuli | ~0.1 sec. | ~0.01 sec. (tone bursts) | Touches sensed as discreet to 20/sec. | Taste ~30 sec. Smell ~20 sec. to 60 sec. | ~1 to 2 sec. nystagmus may perist to 2 min. after rapid changes in rotation. |
| Reaction time for simple muscular movement | ~0.22 sec. | ~0.19 sec. | ~0.15 sec. (for finger motion, if finger is the one stimulated). | — | — |
| Best operating range | 500 to 600μ (green-yellow) 10 to 200 foot-candles | 300 to 6000 cps. 40 to 80 db | — | Taste: 0.1 to 10% concentration. | ~1G acceleration directed head to foot. |
| Indications for use | 1. Spatial orientation required. 2. Spatial scanning or search required. 3. Simultaneous comparisons required. 4. Multidimensional material presented. 5. High ambient noise levels. (Javitz, 1961) | 1. Warning or emergency signals. 2. Interruption of attention required. 3. Small temporal relations important. 4. Poor ambient lighting 5. High vibration or G forces present. (Javitz, 1961) | 1. Conditions unfavorable for both vision and audition. 2. Visual and auditory senses. (Javitz, 1961) | 1. Parameter to be sensed has characteristic smell or taste. (i.e. burning insulation). | 1. Gross sensing of acceleration information. |
| References | Baker and Grether, 1954 Chapanis, 1949 Woodson, 1954 Wulfeck, *et al.*, 1958 | Licklider, 1951 Licklider and Miller, 1951 Rosenblith and Stevens, 1953 Stevens and Davis, 1938 | Bekèsy, 1961 Jenkins, 1951 | Pfaffman, 1951 | Wendt, 1951 |

Table 16 summarizes several characteristics of the human senses which might be most important in system performance (104). Taste and smell are included because of the detrimental effects which may accrue to humans, i.e. distraction, nausea, etc.

Human vision. - Figure 24 shows the relative sensitivity of cones (foveal vision) and rods (peripheral vision) to wave lengths in the range 400-700 $m\mu$ (104). If it be remembered that the majority of the cones are concentrated in the fovea and that cones are largely responsible for detail and color vision, then Figure 24 demonstrates that tasks requiring the discrimination of detail and/or color should be so arranged that images can be projected on the eye (fovea) with a minimum of search on the part of the subjects. Further, the intensities of the objects to be discriminated must be relatively high. On the other hand, since rod vision is relatively more sensitive, tasks which require the detection, without discrimination, of low intensity objects should be so arranged that images fall on the retina away from the fovea. This may require considerable training of the operator.

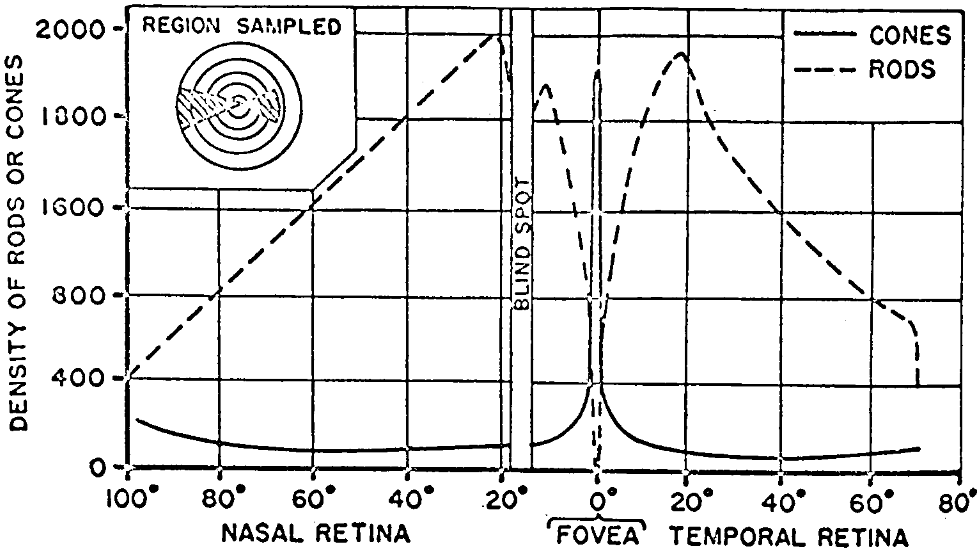



Figure 24. Rod-cone population curve. Density of rods and cones from nasal to temporal edge of the retina.

Figure 25 shows relative visual acuity as a function of retinal position (104). Relative visual acuity is greatest at the fovea and decreases dramatically as the distance from the fovea increases.

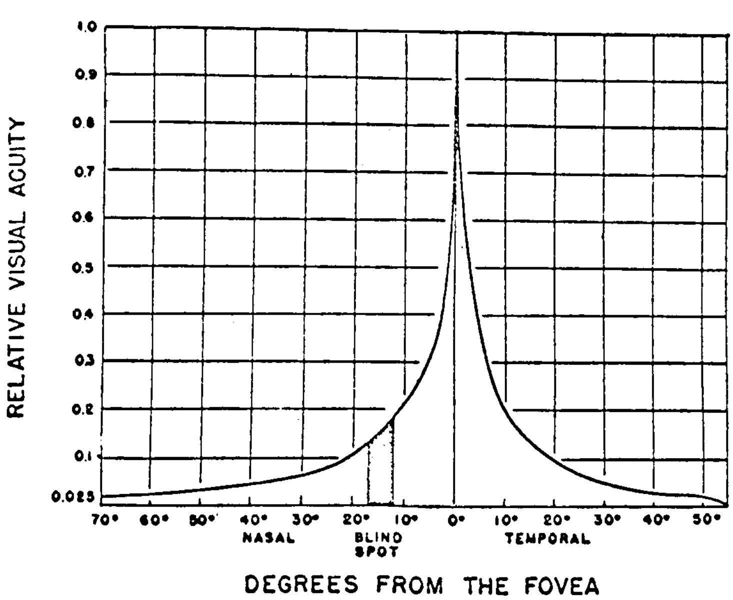



Figure 25. Visual acuity at different retinal positions.

This function supports the conclusions drawn from Figure 24.

Figure 26 shows visual acuity as a function of background luminance for five different locations on the retina; at the fovea and at 1, 4, 15 and 30 degrees with respect to the fovea (64). One of the interesting things about Figure 26 is that when background luminance is less than 6-6.25 $\log \mu\mu$ L, visual acuity is better about $4^{\circ}$ from the fovea, than at the fovea.

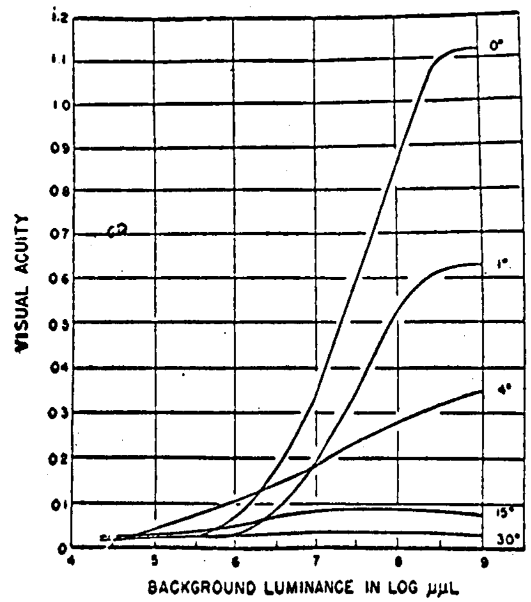



Figure 26. Visual acuity as a function of luminance at various retinal locations.

Figure 27 shows the visual angle of the smallest detail that can be discriminated as a function of background luminance and distance from the fovea (104). The curves are based on a dark object against a light background. Therefore, the loss in visual acuity with decreasing luminance is also a function of contrast (as in everyday behavior).

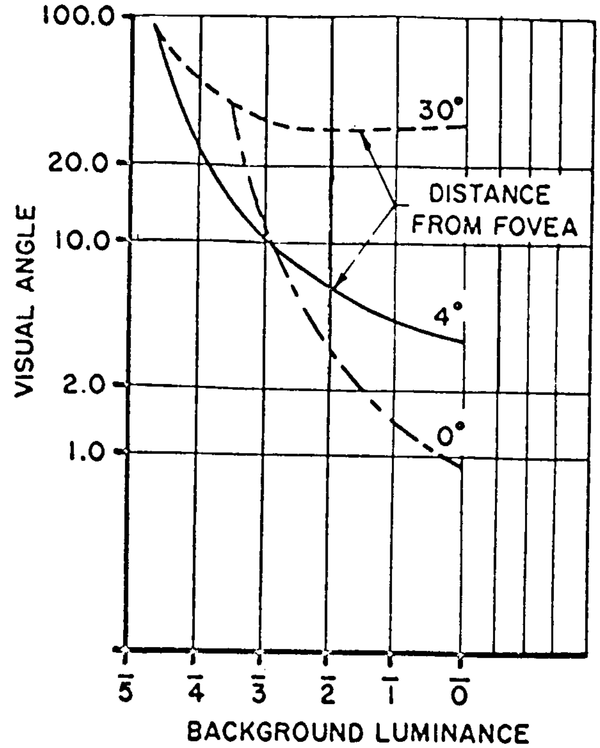



Figure 27. Visual angle of the smallest detail that can be discriminated as a function of background luminance.

Figure 28 shows the probability of detection of a target as a function of the visual angle in minutes which is subtended by that target (5). For these data visual angle is defined as twice the arctan of the ratio of the size of the object measured perpendicular to the line of sight and twice the distance of the object from the observer.

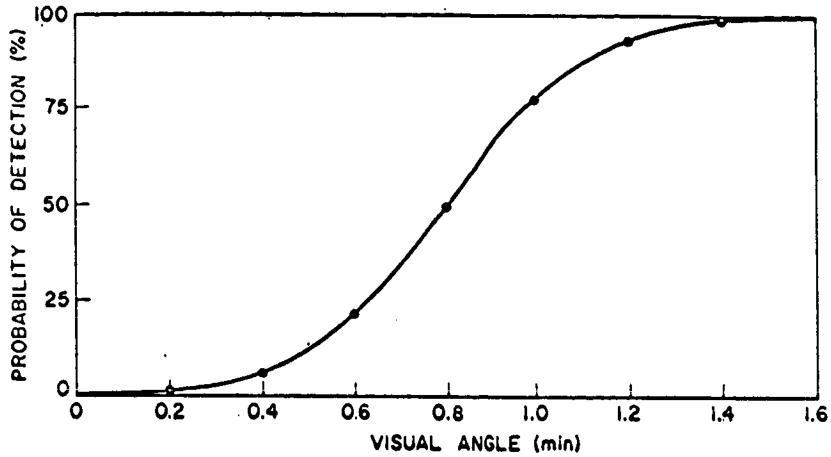



Figure 28. Probability of target detection as a function of target size (visual angle) when target is known.

Figure 29 shows the relationship between contrast (percent), background luminance and the size of a bar (in minutes of visual angle) which can be seen under normal daylight conditions (20).

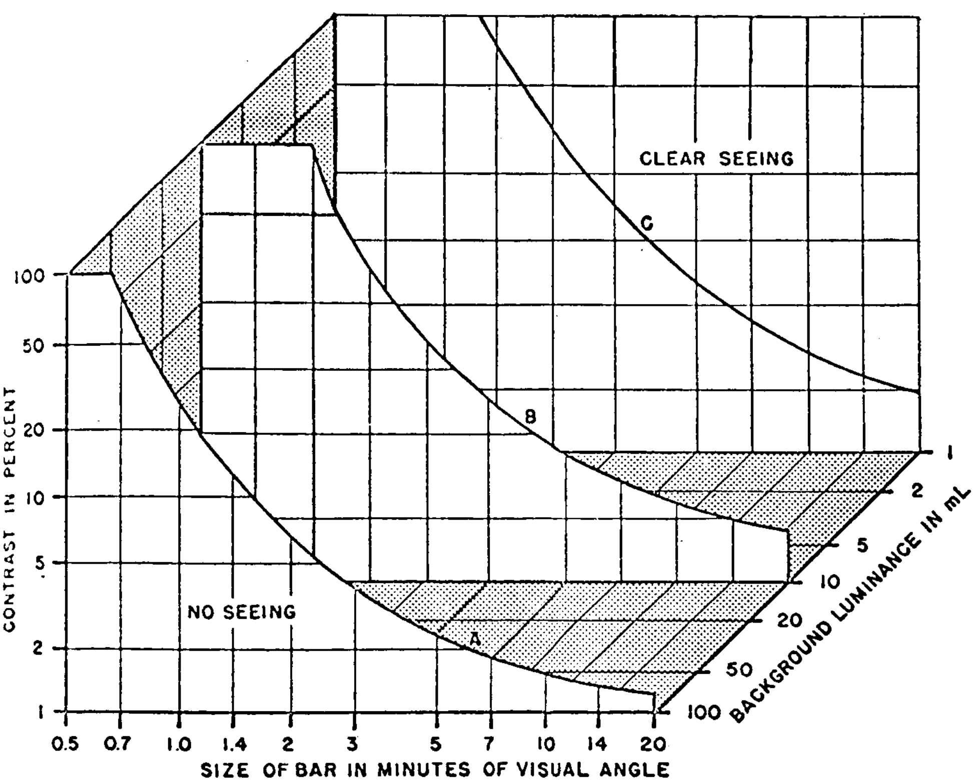



Figure 29. Background luminance and contrast required for bars subtending various visual angles. (Daylight conditions).

Figure 30 shows the smallest brightness contrast that can be seen as a function of background luminance, for objects of four different areas (5). Note the discontinuity where luminance increases to the point of shift from rod to cone vision.

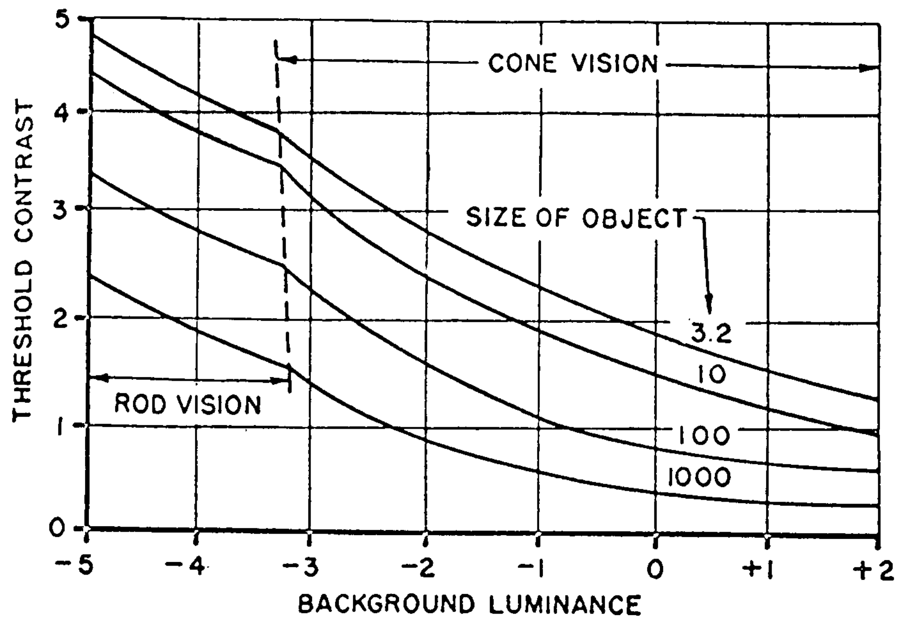



Figure 30. The smallest brightness contrast that can be seen, as a function of luminance.

Figure 31 shows the relationship between visual angle (log min.) and background brightness (log ft-L) for five different degrees of contrast (5). The targets were spots against the background. There is no lower size limit for spots which are lighter than their background. Figure 31 shows the same discontinuity as does Figure 30 with the shift from rod to cone vision.

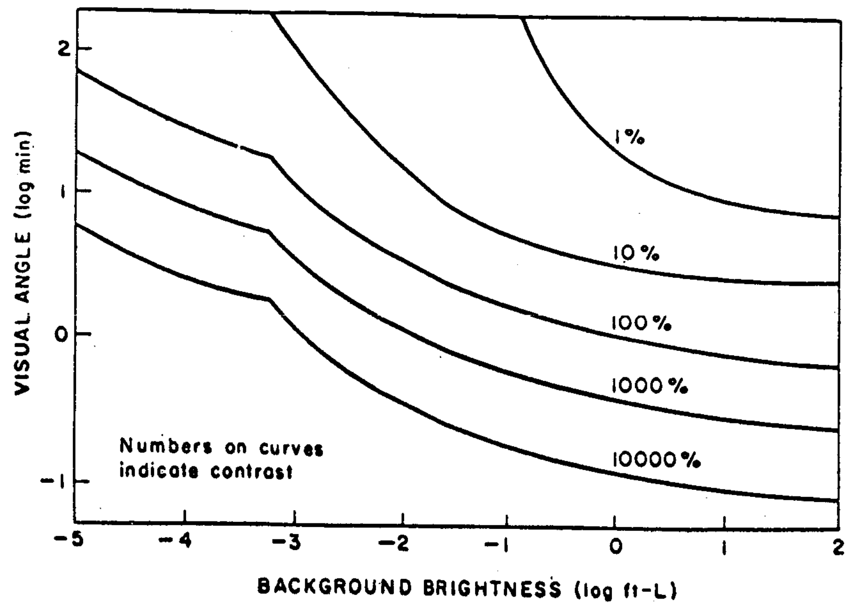



Figure 31. Spot detection as a function of brightness level and brightness contrast.

Figure 32 shows the threshold intensity for four colors as a function of background brightness (47). It is seen that yellow has the highest threshold intensity.

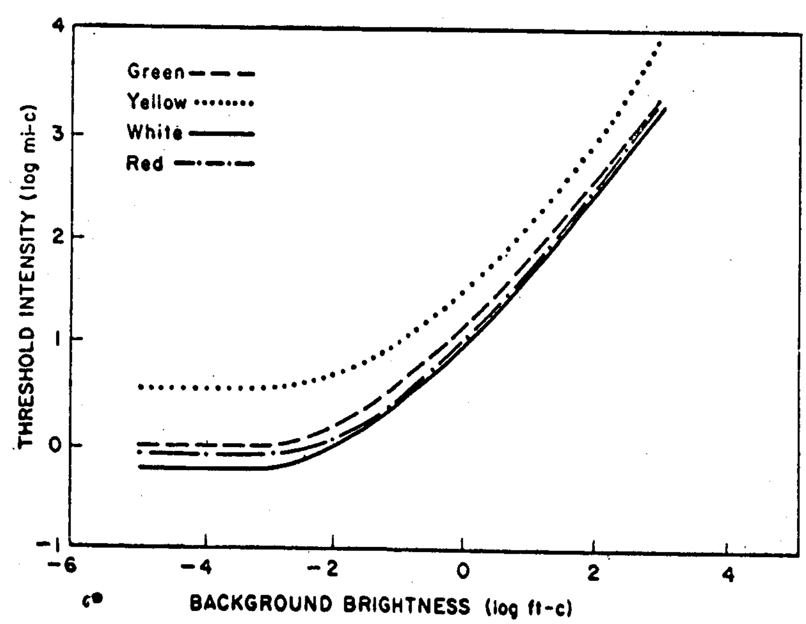



Figure 32. Intensity of point-source signal light of various colors when viewed against neutral background of various brightness.

Figure 33 is a dark adaptation curve (88). It shows the luminance threshold (luminance which can just be seen) as a function of time in the darkness. The luminance threshold drops as one stays longer in the dark. To put it another way, the longer one is adapted to the dark, the smaller the luminance which one can detect.

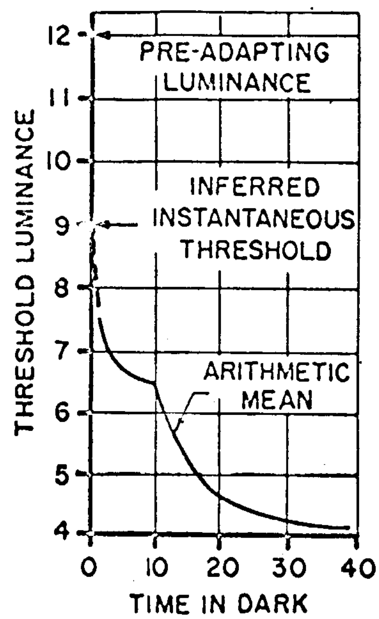



Figure 33. Luminance that can just be seen as a function of time in darkness.

Figure 34 shows threshold data for visual judgment of target motion as a function of the visual angle subtended by the target (4). The smaller the visual angle the farther the target must travel before it is perceived as in motion.

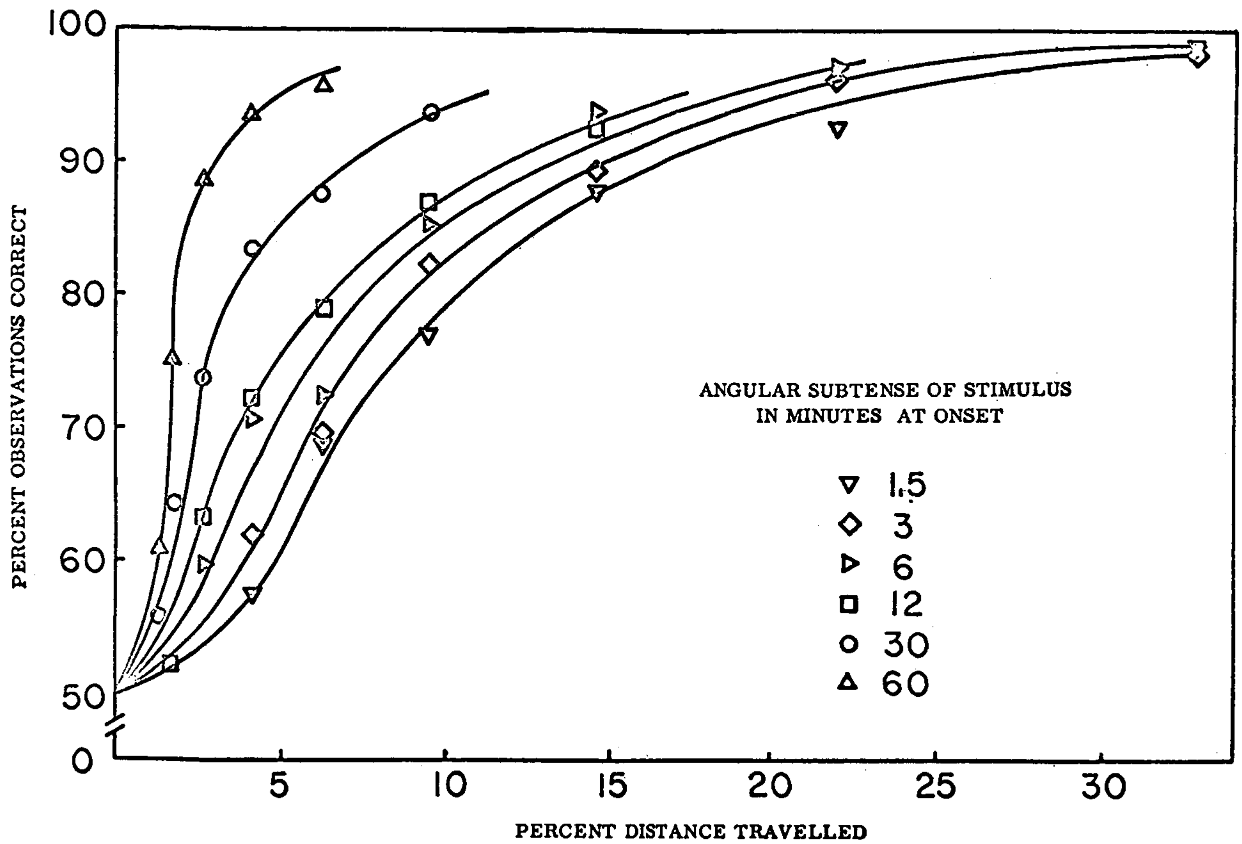



Figure 34. Threshold data for visual judgment of target motion in rendezvous.

Table 17 lists a number of visual variables and the type of visual performance in which it is important to control each (103). For example, if one were concerned with visual acuity, the variable measured would be stimulus size (which could be seen). One would have to control all of the other variables except numbers 9, 11, and 12.

Table 17. Variables which must be controlled when measuring some of the principal kinds of visual performance.

| Type of Visual Performance | Variables to Be Controlled | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Level of Illumination | Region of Retina Stimulated | Stimulus Size | Stimulus Color | Contrast between Test Object and Background | Adaptive State of Eye | Duration of Exposure | Distance at which Measured | Number of Cues Available | Movement | Other Objects in Field | Monocular vs. Binocular | Stimulus Shape |
| Visual acuity | X | X | (MV)[a] | X | X | X | X | X | | X | | | X |
| Depth discrimination | X | | X | X | X | X | X | X | X | X | X | X | |
| Movement discrimination | X | X | X | X | X | X | X | X | X | (MV)[a] | X | | X |
| Flicker discrimination | X | X | X | X | X | X | X | | | | | | |
| Brightness discrimination | X | X | X | X | (MV)[a] | X | X | | | X | | X | X |
| Brightness sensitivity | | X | X | X | (MV)[a] | X | X | | | X | | | X |
| Color discrimination | X | X | X | (MV)[a] | X | X | X | X | X | | X | | |

[a] Variable being measured
(From Wulfeck *et al.*, 1958)

It is recommended that vision be used for (41):

1. Spatial orientation;
2. Rapid scanning;
3. Rapid successive comparisons;
4. Simultaneous comparisons;
5. Frequent reference to information;
6. Fine quantitative discriminations;
7. Multi-dimensional or complex material;
8. Situations with high ambient noise;
9. Situations with rapid air-pressure changes.

Human audition. - Figure 35 shows the threshold of audibility as a function of frequency and sound pressure in decibels (103). Figure 35 shows the rather subtile relationship between audition and the tactile sense.

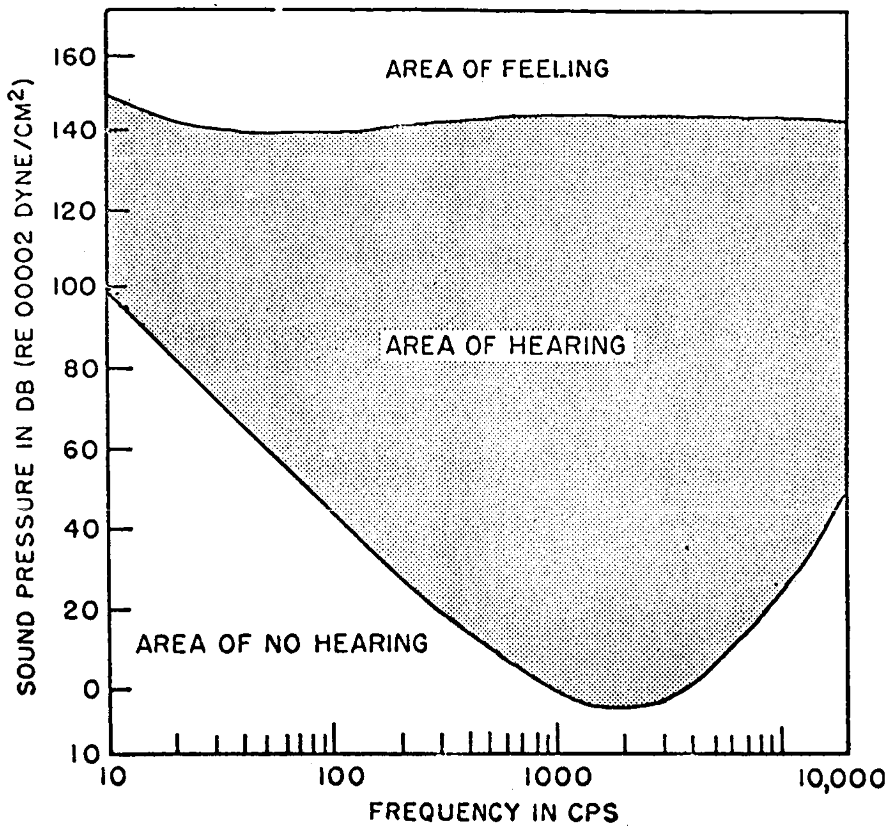



Figure 35. Threshold of audibility as a function of frequency.

Figure 36 shows the effects of frequency of sound stimuli and the increment in frequency on the differential intensity threshold (86). Such information might be valuable in situations of lift-off for predicting protective measures for astronauts.

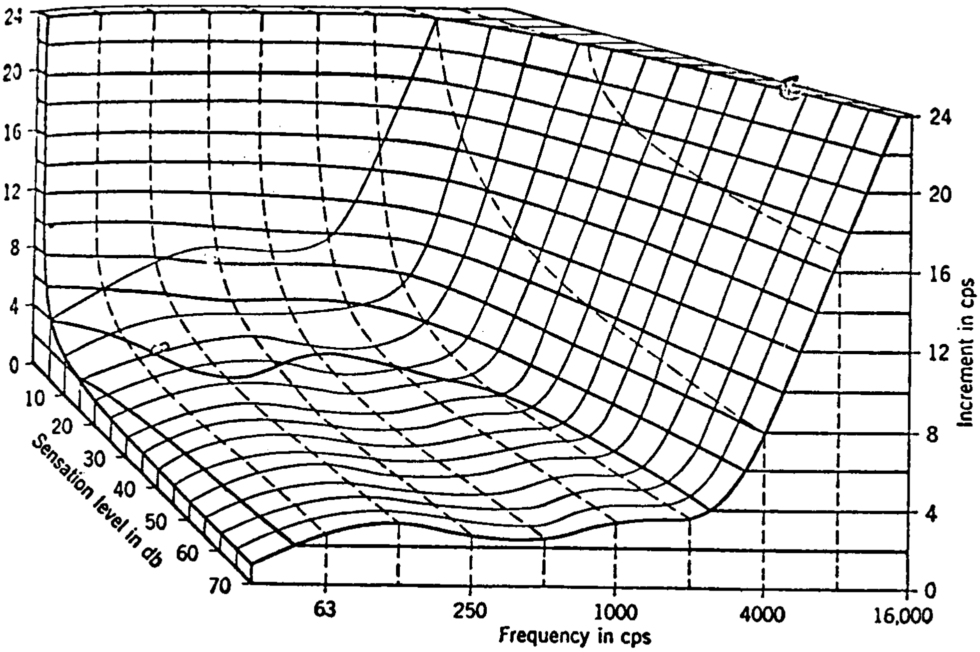



Figure 36. The differential frequency threshold as a function of frequency and intensity of the stimulus.

Figure 37 shows the effect of frequency of sound stimuli and sound pressure in decibels on the differential intensity threshold (79).

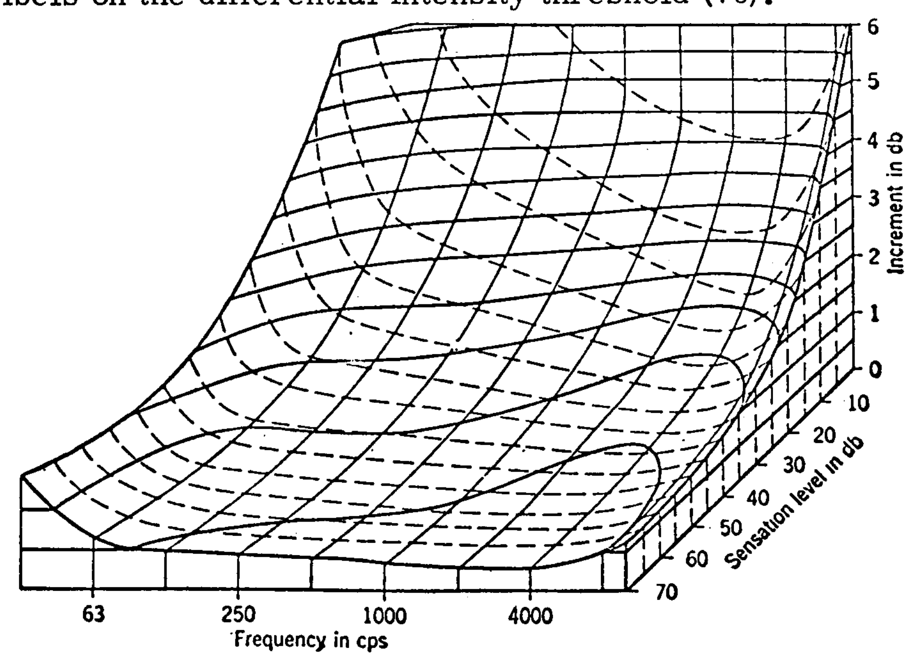



Figure 37. The differential intensity threshold (DL) as a function of the frequency and intensity of the stimulus.

Figure 38 shows the relationship between loudness, intensity of sound in decibels and frequency of the sound stimulus (93).

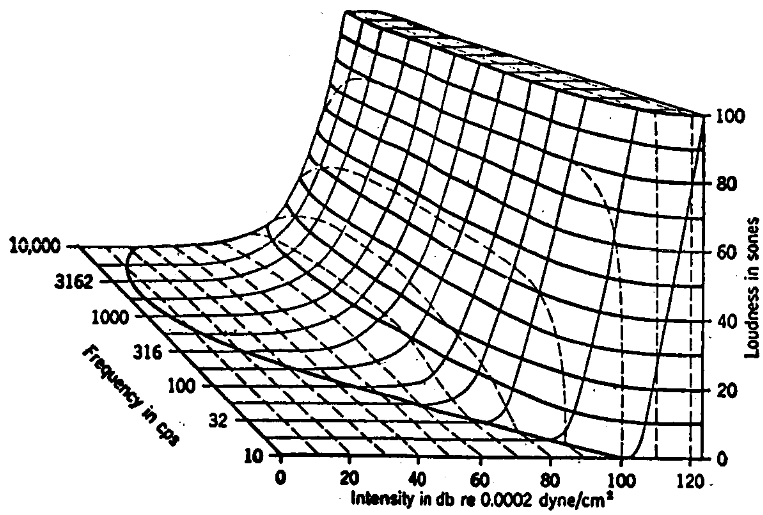



Figure 38. Loudness as a function of intensity and frequency.

Figure 39 shows the relationship between sound pressure level per cycle in decibels and frequency in cycles per second (57). This is called the average speech spectra.

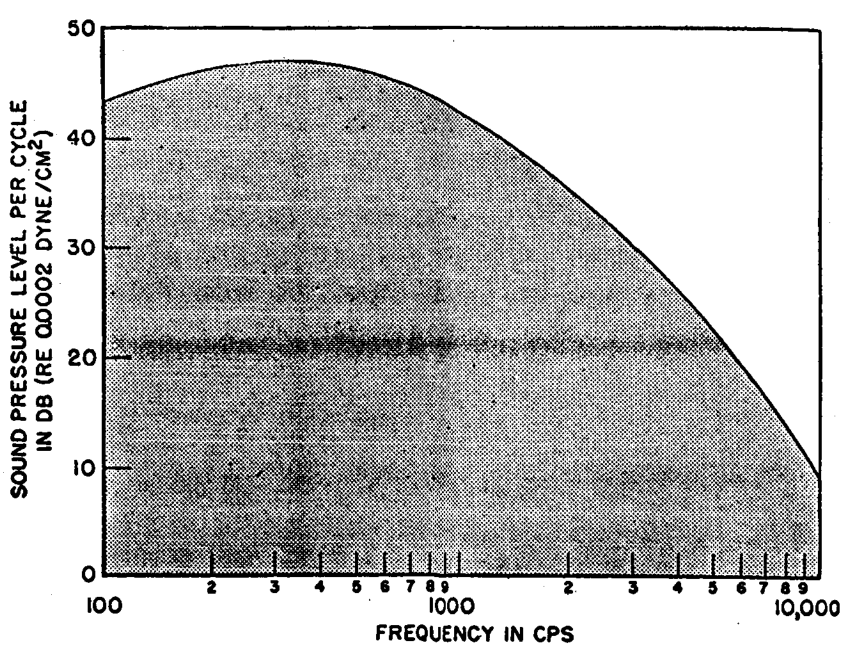



Figure 39. Average speech spectra.

Figure 40 shows the masking effects of random (white) noise on pure tones as a function of frequency in cycles per second (45). The ordinate indicates just audible intensity for the pure tone against the random noise.

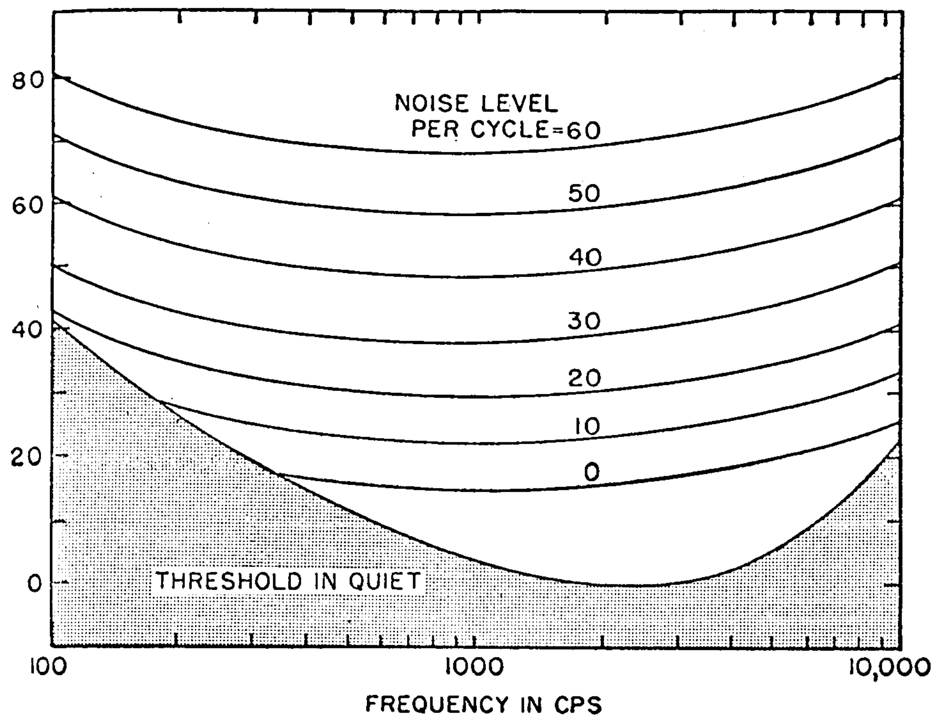



Figure 40. The masking effect of white noise on the perception threshold of pure tones. The ordinate indicates the intensity required for the pure tone to be just audible against the random noise masking of the level shown as the parameter of each curve.

It is recommended that audition be used if (41):

1. A warning or emergency signal is to be detected;
2. Interruption of attention is required;
3. Small temporal relations are important;
4. Lighting conditions are poor;
5. Vision is obstructed;
6. Large vibrations or g-forces are present.

The human tactile sense. - Relatively little use has been made of the tactile sense in any system task. It has been shown (35) that it is possible to use the tactile sense to transmit messages very accurately. Subjects were trained to receive messages when letters were coded according to:

1. Position of stimulation, 5 positions;
2. Duration of stimulation, 3 durations;
3. Amplitude of stimulation, 3 amplitudes.

It was found that subjects could receive messages at the rate of 38 words per minute. This is quite good when one considers that 30 words per minute is considered good for Morse code.

It is recommended that the tactile sense be used when (41):

1. Conditions for both vision and audition are unfavorable;
2. Redundancy above visual and auditory inputs is required;
3. Visual and auditory channels are overloaded and the input material consists of a limited number of discrete categories.

The problem with the use of the tactile sense is that observers will most certainly be doing something with vision or audition, or both. In such a situation it is known that to input information through another channel will degrade response to all channels, unless the information provides only redundancy. In the long run, there are better ways of providing redundancy, especially to the visual channel, than the use of another sensory mode.

The application of force. - Human ability to apply force is small, by comparison with machines, particularly if that force must be relatively large and applied smoothly over some period of time. On the other hand, if the force is small man can apply and direct this force -- usually with the aid of tools -- very smoothly over a remarkable period of time. A good example is the task the dentist performs when he pries a broken tooth out of a jaw. Table 18 shows the hand torque, measured in inch-pounds, and the hand flexion force measured in pounds, which the human can apply (75).

Table 18. Hand torque and hand flexion force which the human can apply with and without full pressure suit.

**Means of Test Results**

| | *Purdue Pegboard†* | | | | *Hand Torque‡* | | | | | | *Hand Flexion§* | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | *Screwdriver* | | *Ball* | | *Knob* | | | |
| | *Right* | *Left* | *Both* | *Assy.** | *Pron.** | *Sup.** | *Pron.** | *Sup.** | *Pron.** | *Sup.** | *Right* | *Left* |
| Without full-pressure suit | 16.83 | 17.66 | 27.00 | 9.79 | 69.17 | 57.50 | 73.33 | 85.83 | 118.33 | 117.50 | 110.83 | 111.66 |
| With full-pressure suit, unpressurized | 8.16 | 8.16 | 12.66 | 3.63 | 62.50 | 45.83 | 70.00 | 74.16 | 118.66 | 140.83 | 78.33 | 80.00 |
| With full-pressure suit, pressurized | 6.00 | 6.83 | 6.16 | 2.00 | 51.66 | 48.66 | 56.66 | 60.83 | 105.50 | 105.83 | 60.00 | 60.83 |

* Abbreviations: Assy. = Assembly; Pron. = Pronation; Sup. = Supination.
† Purdue pegboard measurements indicate number of pins placed in holes by right hand, left hand, and both hands in 30 sec, and the number of assemblies completed in 60 sec.
‡ Hand torque measurements in inch-pounds.
§ Hand flexion measurements in pounds.

Table 18 also shows the decrements in such forces which occur when the subject wears a full pressure suit, with and without full pressure. Such decrements may not appreciably effect control tasks which would be performed in space craft. However, they very likely will hinder the work which can be done by maintenance personnel. It would be desirable to have a tool which would allow the application of force, amplify that force and also anchor the maintenance personnel during the time the force was being applied.

Figure 41 shows the relation between force applied at the hand and velocity for the muscle group causing elbow flexion (44). The dotted curve is a constant power curve, value at 112 ft lb/sec. average power output. The maximum power point is at about 7 ft/sec. and 17 pounds of force.

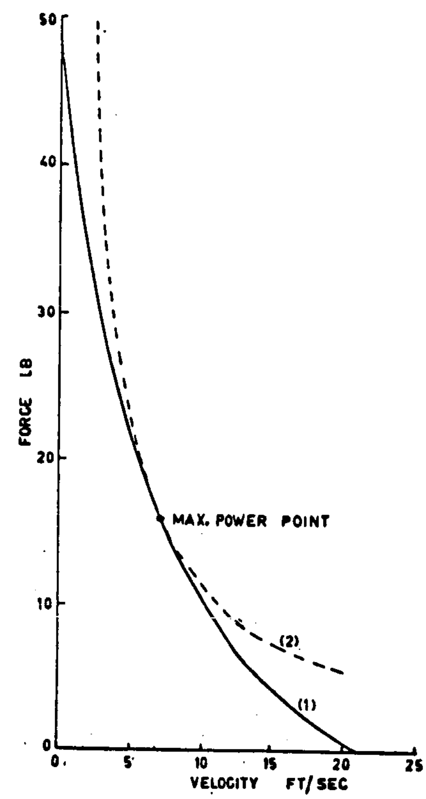



Figure 41. Curve (1) relation between force and velocity for muscle group causing elbow flexion: values apply at the hand.

Curve (2) constant power curve, 112 ft lb/sec.

Figure 42 shows the strength of horizontal push, in pounds, as a function of elbow angle, under five conditions of back support (16). The experiment which generated these data showed a significant elbow angle-times-back support interaction term. Thus, with no back rest elbow angle had no effect. Further, at the smaller elbow angles, there was little or no differencc due to back rest. Maximum back rest effect comes with maximum elbow angle.

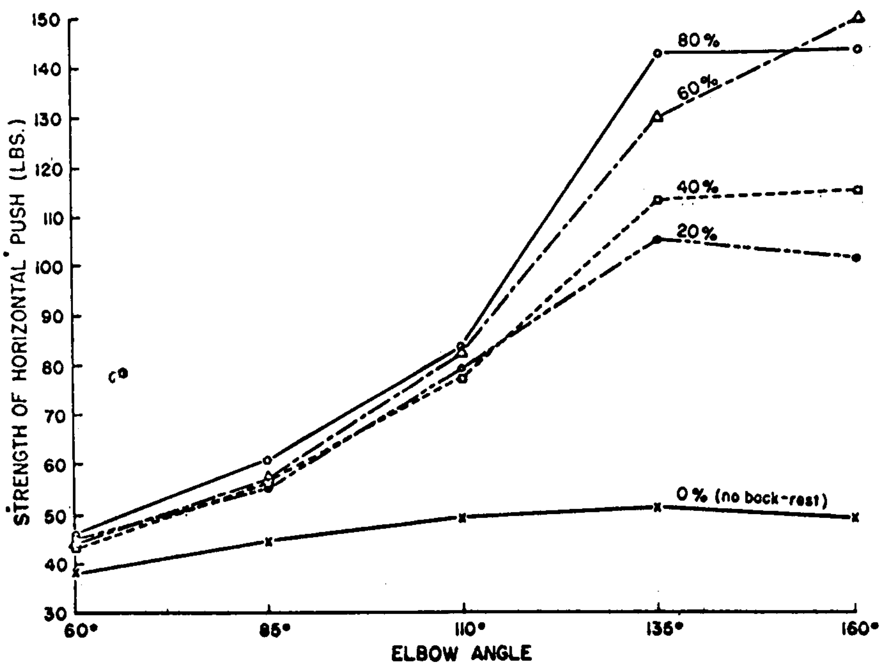



Figure 42. Strength of arm extension (push) at five elbow angles with five conditions of back support.

Table 19 shows the mean maximum force extended by women on handles mounted in emergency exit ports in a simulated aircraft (59). The tabled values are pounds of force. Values of the mean, median, range and first and third quartile are given for each the right, left and preferred choice hand, for three body positions and for a sudden jerk. When force is

Table 19. Mean maximum force applied by women to a 0.3 inch unprotected and a 0.67 inch diameter rubber-covered handle mounted in the exit port. N is 10.

**Unprotected Handle**

| *Position and duration of muscular contraction* | | *Right hand* | | | | | *Left hand* | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | *Mean* | *Median* | *Range* | $Q_1$ | $Q_3$ | *Mean* | *Median* | *Range* | $Q_1$ | $Q_3$ |
| Seated | 5 sec | 52 | 51 | 27–70 | 41 | 66.5 | 43 | 46.5 | 15–66 | 29.5 | 54.5 |
| Standing | 5 sec | 62 | 55 | 41–110 | 48.5 | 74 | 53 | 50 | 32–78 | 44.5 | 65 |
| Standing over passenger | 5 sec | 59 | 52.5 | 40–100 | 45.5 | 77 | 54 | 51 | 30–92 | 43.5 | 63 |
| Jerk | 0.2–0.3 sec | 140 | 130.5 | 68–280 | 85 | 172.5 | 113 | 96 | 71–230 | 73 | 140 |

| | | *Right, left or both hands* | | | | |
|---|---|---|---|---|---|---|
| | | *Mean* | *Median* | *Range* | $Q_1$ | $Q_3$ |
| Choice | 5 sec | 73 | 60.5 | 37–147 | 44 | 105 |

Table 19. (Cont.)

**Rubber-Covered Handle**

| *Position and duration of muscular contraction* | | *Right hand* | | | | | *Left hand* | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | *Mean* | *Median* | *Range* | $Q_1$ | $Q_3$ | *Mean* | *Median* | *Range* | $Q_1$ | $Q_3$ |
| Seated | 5 sec | 69 | 72.5 | 35–90 | 51 | 85.5 | 53 | 56 | 17–77 | 34 | 75 |
| Standing | 5 sec | 76 | 72.5 | 42–115 | 45.5 | 110 | 72 | 72.5 | 32–120 | 40.5 | 96 |
| Standing over passenger | 5 sec | 69 | 61 | 37–108 | 48.5 | 97.5 | 67 | 64 | 33–120 | 47.5 | 82.5 |
| Jerk | 0.2–0.3 sec | 168 | 168 | 73–316 | 122 | 187.5 | 143 | 136 | 75–264 | 107 | 174.5 |

| | | *Right, left or both hands* | | | | |
|---|---|---|---|---|---|---|
| | | *Mean* | *Median* | *Range* | $Q_1$ | $Q_3$ |
| Choice | 5 sec | 80 | 70 | 48–145 | 50.5 | 107.5 |

applied smoothly, over a period of five seconds, the standing position tends to give the highest values for mean and median force applied. However, this value has the greatest range, and hence, will have a higher variability. It is seen that the force which can be applied by a sudden jerk, which is held for 0.2-0.3 seconds, is an order of magnitude greater than the smoothly applied force. Reference 66 presents a series of tables of the maximum force which can be exerted by the human in lifting, pulling, pushing, with the arm and leg from different bodily positions.

## Human Performance

Introduction. - The statement was made in Chapter II that man has unique capabilities and limitations which should be capitalized upon when considering his role in a system. It will be the purpose of this section to discuss these unique capabilities and limitations under four headings:

1. Human limitations;
2. Man excells:
3. Man is required;
4. Enhancing human performance reliability.

However, it is necessary at the outset to qualify what is to follow. First, the literature contains many statements which compare men and machines. These are two very large classes of things. It may be expedient from a political point of view to consider that all men are born equal. However, from a practical point of view, it is not true. Further, shortly after birth they diverge in a variety of ways. Thus, what a particular human being is, what he can bring to a particular system task and the ease with which he can be integrated into that task, are a function of what he was born with and of the sum total of the experiences he has had before being assigned to the system. Initial selection is one of the most important processes in filling crew requirements for any responsible system task. One of the problems with a good bit of the data on human performance is the selection of subjects. Frequently, people who are handy at the time the experiment is to be conducted are the subjects used. An example in the area of aviation research is the use of college students to estimate the ability of trained pilots to perform visual perceptual judgments (98). The subjects used to help make a decision about man's role in a system should always be representative of the population from which the system operators will be drawn.

On the other hand, all machines are not IBM 7090's, fortunately. Complex electronic equipments of the same series differ among themselves more than do human beings selected and trained to perform complex system tasks (3, 13, 18, 55, 61, 80, 86, 101). Similarly, the class of machines called computers vary in complexity from the H-W Electronics 15K to the IBM 7090, both of which are classed as general purpose solid state computers. They compare as follows (21).

| | HW-15K | IBM-7090 |
|---|---|---|
| Add Time, microseconds | 700 | 4.4 |
| Storage Cycle, microseconds | 16700 | 2.2 |
| Storage, computer words | 4000 | 17,500 |
| Type of storage | Drum | Core & Drum |

| | HW-15K | IBM-7090 |
|---|---|---|
| Word size | 24 binary | 36 binary |
| Buffering | None | MRWC |

The upshot of this discussion is that men differ among themselves and that machines of the same class differ among themselves more than do men. The conclusion seems inescapable, except for making the broadest possible comparisons, that when comparing man and machines one should specify the population from which the man is to be drawn and the specific characteristics of the machine under comparison. No one would argue with the statement that computers can perform arithmetic computations faster than men. On the other hand, some computers perform arithmetic computations faster than other computers.

A second qualification as regards the comparison of men and machines is concerned with preparing the man or machine for use in the system. In the case of the man there are problems of selection, training and pre-operational evaluation. In the case of the machine there are problems of design, construction and pre-operational evaluation. In either case it is necessary to specify intended use, performance criteria and minimum reliability requirements before the chain may be started. In both cases there is considerable interaction between selection and training, in the case of man, and between design and construction, in the case of the machine. In the comparison of man and computers, human training is analogous to computer programming. The human must learn a basic set of mental and physical skills which serve as a foundation for more complex and specialized learning and task performance. The system programs for a computer are analogous to these basic skills of the human. The learning of more complex and specialized task performance, on the part of the human is analogous to the specific -- non-system -- programs which must be written for the computer. Just as human performance can be modified by training, within the limits of the basic set of skills, so may the computer performance be modified by writing new programs, within the constraints of the available system programs. While the basic skills of the human tend to remain relatively constant, it is possible to modify these, e.g. learning a foreign language. The majority of the change in human task performance is in the specialized tasks. Similarly with the computer, while system programs may be changed, it is specific programs which are continually being written, updated and improved.

A second analogy to the training which humans frequently receive is the modification to change or improve the operating characteristics of machines. A modification to an operating piece of equipment requires that the entire chain of design, construction and pre-operational evaluation begin anew. Modifications usually arise because of inadequacies in the original piece of equipment. Such modifications run the gamut from relatively minor changes to the obsolescence of a piece of equipment, e.g. the AN/FSP-20 radar replacing the AN/FSP-6 radar, in the air defense unit. Few of the articles in the literature considered these processes. However, these processes are not accomplished for free, either for man or machine. Preparing either man or machine to fill a role in a systems costs money and requires time, talent and facilities.

A third qualification is the requirements for the use of man or a machine. Here one must consider such things as special environments, space requirements, weight, power, preventative maintenance to maintain reliability (motivation, if one is speaking of humans). In most systems, the human does not need a special environment. However, most complex electronic equipments do need a special environment. In such cases the human operator benefits from the demands of the machine. With the advent of solid state electronics, the demands for a special environment are not so stringent. However, they are not entirely removed.

With the advent of high altitude and space flight, the system itself operates in a highly specialized environment. In such cases man requires that the operational environment be modified to conform to the limits of his ecological constraints. As long as space craft are small, with a minimum of electronic gear, the equipment will benefit from the human requirement. But as space craft become larger, with more and more electronic gear, the requirement for the special environment will be contributed by both man and machine.

In terms of the capacity and diversity for performance which man offers, he requires relatively little space for most system tasks. This statement assumes that man takes his rest and recreation at a point remote from his system task performance. If the system must also provide for human rest and recreation, then man's space requirements increase considerably. In the case of man there is likely a strong relationship between space requirements in such a situation and the nature and duration of the mission. Space requirements will increase with increased mission duration, up to a maximum, and remain constant thereafter.

Space requirements for a machine are independent of mission duration. These space requirements are composed of that space occupied by the machine as such and the adjacent space required for all maintenance. Despite the enormous strides which have been made in miniaturization and packaging equipments still require a great deal of space.

Both man and machine place constraints on the system in terms of the weight they bring with them and the power they require for operation. However, in relation to capacity for performance, man has the edge, on both counts. Electronic and other equipments are generally heavy and they require more equipment to supply them with power. Man is light per unit of capability and he requires only about 100 watts of power per day (33). Furthermore, in ground based systems and short duration flight missions, he brings that power with him. However, in space craft with long duration missions, man's quantitative power supply requirements may become formidable. Further, qualitatively, man's power supply requirements are very complex.

In the case of the human performance, reliability is maintained by social custom and constraints. The job that is done or the position filled, carries with it a certain status or prestige value. If a man occupies a low status position he is encouraged to do well, improve himself and move up the status ladder. If the man accepts the social context in which the position is found, all is well. If he does not, then coercion or appeals to pride, team fellowship or patriotism may serve as poor seconds. Another way to maintain motivation is through remuneration for services. This is usually in the form of money, which contributes to social status. The crux of the matter is to get the individual to accept the subculture of the system tasks.

A fourth area for consideration is maintenance and repair. Both man and machine place heavy requirements on either a system or its context for maintenance and repair. Data to make trade-offs in this area must be prepared before an adequate comparison may be made.

The foregoing qualifications may be summarized as follows. In considering a trade-off between man and machine, where performance capabilities are not at issue, one should consider:

1. The population from which system operators will be drawn;
2. The specific characteristics of the machines under consideration;
3. The costs of selection and training of humans as compared with the costs of design and construction of equipment;
4. The costs of potential continued training for humans as compared with the costs of potential modification and reprogramming for equipments;
5. Special environmental requirements of man and machine;
6. Space requirements of man and of machine;
7. Weight and power requirements of man and machine;

8. Reliability (motivation) and preventative maintenance;
9. Cost of maintenance and repair.

With the foregoing qualifications in mind we will proceed with the review of the literature. Since the literature on the topics of concern tends to be qualitative in nature, the summary will be accomplished by a series of listings.

Human limitations.-

| Man | Machine |
|---|---|
| 1. Men are poor monitors of infrequent events or of events which occur frequently over a long period of time. | 1. Machines can be constructed to detect reliability infrequent events or events which occur frequently over a long period of time. |
| 2. The human has limited channel capacity. | 2. Machines may have as much channel capacity as can be afforded. |
| 3. Humans are subject to a coriolis effect, motion sickness. | 3. Machines are not subject to a coriolis effect. |
| 4. Man is not well suited to data coding, amplification or transformation tasks. | 4. Machines are well suited to these kinds of tasks. |
| 5. Man has extremely limited short term (buffer) memory for factual material. | 5. Machines may have as much buffer memory as can be afforded. |
| 6. Human performance is degraded by fatigue and boredom. | 6. Machine performance is degraded only by wearing out or by lack of calibration. |

| | Man | | Machine |
|---|---|---|---|
| 7. | Unselected individuals differ greatly among themselves. | 7. | There are no unselected machines. |
| 8. | Human performance is degraded by long duty periods, repetitive tasks and cramped or unchanged positions. | 8. | Machines may be built which are less affected by long duty periods, perform repetitive tasks well, but some are restricted as to position (orientation). |
| 9. | Man saturates quickly in terms of the number of things he can do and in the duration of his effort. | 9. | Machines can do one thing at a time so fast that they seem to do many things at once, for a long period of time. |
| 10. | Man may introduce errors by identification, redintegration or closure. | 10. | Machines do utilize these processes. |
| 11. | Expectation or cognitive set may lead an operator to see what he expects to see. | 11. | Machines do not exercise these processes. |
| 12. | Much of human mobility is predicated on gravity. | 12. | Machines may be built which perform independently of gravity. |
| 13. | Humans have low toleration for g-forces. | 13. | Machines are unaffected by g-forces. |
| 14. | Man can generate only relatively puny forces, and cannot exert a large amount of force smoothly. | 14. | Machines can generate and exert forces as needed. |

| | Man | | Machines |
|---|---|---|---|
| 15. | Man will require a review or rehearsal period before making decisions based on items in memory. | 15. | Machines go directly to the item in memory required for the decision. |
| 16. | When performing a tracking task man needs frequent re-programming. He does best when changes are under 3 radians/second. | 16. | Machines do not have such limitations. |
| 17. | Man has a built-in response latency, about 200 microseconds in a go/no-go situation. | 17. | Machines need not have a response latency. |
| 18. | Man is not well adapted to high speed accurate search of large volumes of information. | 18. | Computers are built to do just this. |
| 19. | Man does not always follow an optimum strategy. | 19. | Machines will always follow the strategy which is built into them. |
| 20. | Man has physiological, psychological and ecological needs. | 20. | Machines have only ecological needs. |
| 21. | Men are subject to anxiety about their safety and about conditions of their environment. | 21. | Machines do not consider safety or aspects of their environment. |
| 22. | Man is dependent upon his social environment, both present and remembered. | 22. | Machines have no social environment. |
| 23. | Man's diurnal cycle imposes cyclic degradation of behavior. | 23. | The machine cycle may be longer than 24 hours. |
| 24. | Interpersonal problems develop among humans. | 24. | No interpersonal problems among machines. |

Man excells.-

| | Man | | Machine |
|---|---|---|---|
| 1. | Man is able to recognize and use information redundance (pattern) in the real world to simplify complex situations. | 1. | Machines have limited perceptual constancy and are very expensive. |
| 2. | Man has high tolerance for ambiguity, uncertainty and vagueness. | 2. | Machines are highly limited by ambiguity and uncertainty in the input. |
| 3. | Man can interpret an input signal accurately even when subject to distraction, high noise or message gap. | 3. | Machines perform well only in a clean environment. |
| 4. | Man is a selecting mechanism and must be set to sense specific items. | 4. | Machines are sensing mechanisms. |
| 5. | Man has very low absolute thresholds for vision, audition and the tactile sense. | 5. | Machines may have the same capability but only at great expense. |
| 6. | Man has excellent long term memory for related events. | 6. | Machines can have this property, but are very expensive. |
| 7. | Man can develop a high flexibility for task performance. | 7. | Machines are inflexible in a task performance situation. |
| 8. | Man has the ability to improvise and exercise judgment based on long term memory and recall. | 8. | Machines do not possess these properties; they are best at routine functions. |
| 9. | Man performs well under transient overload; his performance degrades gracefully. | 9. | Machines stop under overload conditions. |

| | Man | | Machine |
|---|---|---|---|
| 10. | Man can make inductive decisions in novel situations; has the ability to generalize. | 10. | Machines have little or no capability for induction or generalization. |
| 11. | Man can modify his performance as a function of experience; he can "learn to learn." | 11. | Trial and error behavior is not characteristic of machines. |
| 12. | Man can override his own actions should the need arise. | 12. | Machines can only do what they are built to do. |
| 13. | Man is reasonably reliable. He can add reliability to system performance by selection of alternatives. | 13. | Machines are reliable only at the expense of increased complexity and cost; then only for routine functions. |
| 14. | Man complements the machine in the sense that he can use it in spite of design failures, use it for a different task or use it more efficiently than it was designed for. | 14. | Machines have no such capability. |
| 15. | Man complements the machine in the sense that he functions as an aid in sensing, extrapolating, decision making, goal setting for research, monitoring and evaluating the output. | 15. | Machines do not have this capacity for different performance. |
| 16. | Man has the ability to acquire and report information which is incidental to the primary mission. | 16. | Not so machines. |

| Man | | Machine | |
|---|---|---|---|
| 17. | Man is capable of performing time contingency analyses and predicting events in unusual situations. | 17. | Corresponding machines do very poorly. |
| 18. | Man is relatively inexpensive for corresponding complexity. He is in good supply, but must be trained. | 18. | Machines are limited in terms of complexity and supply by cost and time. |
| 19. | Man is light in weight and small in size for function achieved. | 19. | Machines with functional equivalence of man require more weight, power and cooling facilities. |
| 20. | Man is easy to maintain. He demands a minimum of "in task" extras. | 20. | Maintenance problems become disproportionately serious as complexity increases. |

Man is required. - Man is necessary to enhance system reliability. Significant human capabilities which cannot be duplicated by a machine in so small and reliable a package (80) include:

1. Selection among alternative ways of achieving a mission;
2. Integrating a large amount of information gathered from experience and bringing it to bear in a novel situation;
3. Sensitivity to a wide range of stimulus patterns;
4. Capability to detect signals through noise;
5. Capability to act as an intermittent servo in the performance of a number of different systems or equipments.

In complex systems man makes the most significant contribution to output consistency (55).

1. Human can learn to adapt to changes in the system input;
2. Where the relations between input and output may require re-structuring in the course of mission accomplishment;
3. Where the form and/or content of all inputs and outputs cannot be specified ahead of time;
4. Where all operations cannot be reduced to logical preset procedures;
5. Man excells at comprehending complex data presented symbolically, from a non-prescribed universe.

Man makes possible a more diversified system mission. His ability to perform a variety of functions and to utilize alternate means gets more accomplished:

1. Multiple mission performance;
2. Recallable mission attempts;
3. Less vulnerable mission accomplishment;
4. Vehicles can be returned for re-use;
5. Man can translate uncertainty into probability and deal with low probability/high value exigencies;
6. Man can develop a "behavioral strategy" when no optimum strategy can be specified.

Man has this ability to make and report unique observations and experiences:

1. Observations on his own performance;
2. Observations on system performance;

3. Observations of a scientific nature;
4. Incidental intelligence.

Man is required to perform preventative maintenance, trouble-shoot and repair machines.

1. Problem solving;
2. Compensate for inadequate design;
3. Select an appropriate alternative means.

Enhancing human performance reliability. - Human performance reliability can be enhanced in at least four ways:

1. Selection of operators;
2. Training of operators;
3. Motivation of operators;
4. Optimizing task performance situation.

Selection, training and motivation are highly interrelated. Proper selection is important to training and motivation. Operators must possess specific skills if the training they are to receive is to be maximally useful. On the other hand, motivation is dependent upon the degree to which the operator accepts the subculture of task accomplishment. Hence it is important to select individuals who are most likely to accept such a subculture.

It is also in the areas of selection, training and motivation that it is possible to do human engineering, in the full meaning of the term. It is in these areas that the man may be prepared to perform effectively. The conventional usage of the term "human engineering" is with respect to the optimization of the task performance situation. This is more aptly described as adjusting the work situation to suit the man; not human engineering.

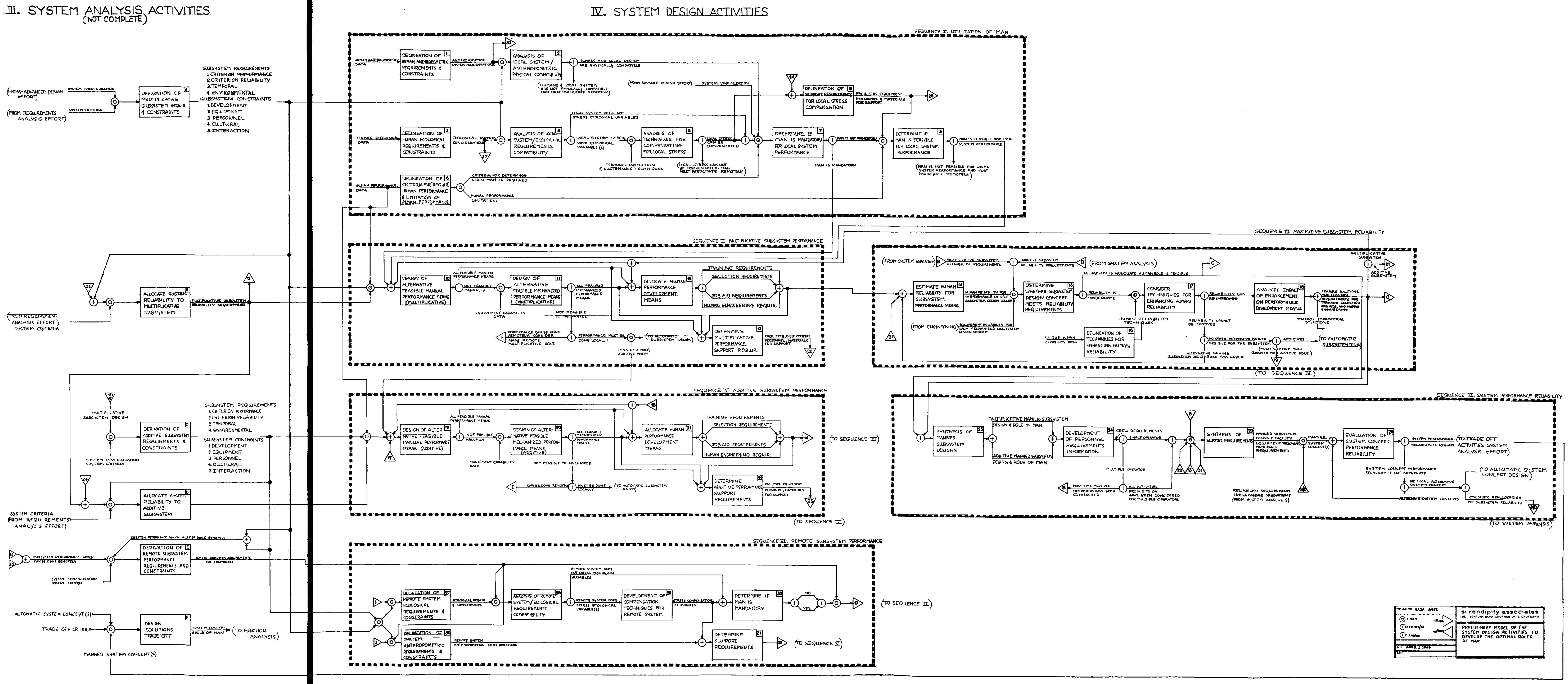
Before any human performance can be enhanced it is necessary to know what performance is to be enhanced. All of this pre-supposes that the roles of man have been determined; a desirable performance means has been chosen; that the reliability to be required of that means has been specified; and that it is known how each performance means for man's roles in the system is related to each other performance means. Such information may be used to specify the kinds of skills which man will have to possess to operate effectively in the system.

The next step, or a step concurrent with skill specification and interaction, is the determination of the characteristics of the subculture of system operation. It will be desirable to determine such things as:

1. Social status and hierarchy of the various system tasks;
2. Acceptable routes for ascending in the status hierarchy;
3. Upper limits on hierarchical ladder;
4. Distribution of responsibility and authority in relation to role status;
5. Standard of living associated with system task performance.
6. Attitudes of the larger social context towards the system and system personnel.

Given information on skill requirements, subculture and socio-economic level of the operators, one can then begin to determine how to merge these two sets of requirements to specify:

1. selection criteria;
2. training requirements;
3. minimum performance adequacy;
4. training evaluation procedures;
5. how to achieve acceptance;
6. how training will contribute to motivation.


III. SYSTEM ANALYSIS ACTIVITIES (NOT COMPLETE)
IV. SYSTEM DESIGN ACTIVITIES
SEQUENCE I. UTILIZATION OF MAN
SEQUENCE II. MULTIPLICATIVE SUBSYSTEM PERFORMANCE
SEQUENCE III. MAXIMIZING SUBSYSTEM RELIABILITY
SEQUENCE IV. ADDITIVE SUBSYSTEM PERFORMANCE
SEQUENCE V. SYSTEM PERFORMANCE RELIABILITY
SEQUENCE VI. REMOTE SUBSYSTEM PERFORMANCE
(FROM ADVANCED DESIGN EFFORT)
(FROM REQUIREMENTS ANALYSIS EFFORT)
DERIVATION OF MULTIPLICATIVE SUBSYSTEM REQUIR. & CONSTRAINTS
SUBSYSTEM REQUIREMENTS
1 CRITERION PERFORMANCE
2 CRITERION RELIABILITY
3 TEMPORAL
4 ENVIRONMENTAL
SUBSYSTEM CONSTRAINTS
1 DEVELOPMENT
2 EQUIPMENT
3 PERSONNEL
4 CULTURAL
5 INTERACTION
ALLOCATE SYSTEM RELIABILITY TO MULTIPLICATIVE SUBSYSTEM
(FROM REQUIREMENT ANALYSIS EFFORT) SYSTEM CRITERIA
DERIVATION OF ADDITIVE SUBSYSTEM REQUIREMENTS & CONSTRAINTS
ALLOCATE SYSTEM RELIABILITY TO ADDITIVE SUBSYSTEM
SYSTEM CRITERIA (FROM REQUIREMENTS ANALYSIS EFFORT)
DERIVATION OF REMOTE SUBSYSTEM PERFORMANCE REQUIREMENTS AND CONSTRAINTS
AUTOMATIC SYSTEM CONCEPT (S)
TRADE OFF CRITERIA
DESIGN SOLUTIONS TRADE OFF
(TO FUNCTION ANALYSIS)
MANNED SYSTEM CONCEPT (S)
DELINEATION OF HUMAN ANTHROPOMETRIC REQUIREMENTS & CONSTRAINTS
ANALYSIS OF LOCAL SYSTEM / ANTHROPOMETRIC PHYSICAL COMPATIBILITY
DELINEATION OF HUMAN ECOLOGICAL REQUIREMENTS & CONSTRAINTS
ANALYSIS OF LOCAL SYSTEM/ECOLOGICAL REQUIREMENTS COMPATIBILITY
ANALYSIS OF TECHNIQUES FOR COMPENSATING FOR LOCAL STRESS
DELINEATION OF CRITERIA FOR REQUIR. HUMAN PERFORMANCE & LIMITATION OF HUMAN PERFORMANCE
DELINEATION OF SUPPORT REQUIREMENTS FOR LOCAL STRESS COMPENSATION
DETERMINE IF MAN IS MANDATORY FOR LOCAL SYSTEM PERFORMANCE
DETERMINE IF MAN IS FEASIBLE FOR LOCAL SYSTEM PERFORMANCE
MAN IS MANDATORY
(MAN IS NOT FEASIBLE FOR LOCAL SYSTEM PERFORMANCE AND MUST PARTICIPATE REMOTELY)
DESIGN OF ALTERNATIVE FEASIBLE MANUAL PERFORMANCE MEANS (MULTIPLICATIVE)
DESIGN OF ALTERNATIVE FEASIBLE MECHANIZED PERFORMANCE MEANS (MULTIPLICATIVE)
ALLOCATE HUMAN PERFORMANCE DEVELOPMENT MEANS
TRAINING REQUIREMENTS
SELECTION REQUIREMENTS
JOB AID REQUIREMENTS
HUMAN ENGINEERING REQUIR.
DETERMINE MULTIPLICATIVE PERFORMANCE SUPPORT REQUIR.
ESTIMATE HUMAN RELIABILITY FOR SUBSYSTEM PERFORMANCE MEANS
DETERMINE WHETHER SUBSYSTEM DESIGN CONCEPT MEETS RELIABILITY REQUIREMENTS
CONSIDER TECHNIQUES FOR ENHANCING HUMAN RELIABILITY
DELINEATION OF TECHNIQUES FOR ENHANCING HUMAN RELIABILITY
ANALYZE IMPACT OF ENHANCEMENT ON PERFORMANCE DEVELOPMENT MEANS
(FROM SYSTEM ANALYSIS)
(FROM ENGINEERING)
(TO AUTOMATIC SUBSYSTEM DESIGN)
(TO SEQUENCE IV.)
DESIGN OF ALTERNATIVE FEASIBLE MANUAL PERFORMANCE MEANS (ADDITIVE)
DESIGN OF ALTERNATIVE FEASIBLE MECHANIZED PERFORMANCE MEANS (ADDITIVE)
DETERMINE ADDITIVE PERFORMANCE SUPPORT REQUIREMENTS
(TO SEQUENCE III)
(TO SEQUENCE V)
SYNTHESIS OF MANNED SUBSYSTEM DESIGNS
MULTIPLICATIVE MANNED SUBSYSTEM DESIGN & ROLE OF MAN
ADDITIVE MANNED SUBSYSTEM DESIGN & ROLE OF MAN
DEVELOPMENT OF PERSONNEL REQUIREMENTS INFORMATION
CREW REQUIREMENTS
SYNTHESIS OF SUPPORT REQUIREMENTS
EVALUATION OF SYSTEM CONCEPT PERFORMANCE RELIABILITY
(TO TRADE OFF ACTIVITIES SYSTEM ANALYSIS EFFORT)
(TO AUTOMATIC SYSTEM CONCEPT DESIGN)
(TO SYSTEM ANALYSIS)
DELINEATION OF REMOTE SYSTEM ECOLOGICAL REQUIREMENTS & CONSTRAINTS
DELINEATION OF SYSTEM ANTHROPOMETRIC REQUIREMENTS & CONSTRAINTS
ANALYSIS OF REMOTE SYSTEM/ECOLOGICAL REQUIREMENTS COMPATIBILITY
DEVELOPMENT OF COMPENSATION TECHNIQUES FOR REMOTE SYSTEM
DETERMINE IF MAN IS MANDATORY
DETERMINE SUPPORT REQUIREMENTS
(TO SEQUENCE II)
(TO SEQUENCE V)
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PRELIMINARY MODEL OF THE SYSTEM DESIGN ACTIVITIES TO DEVELOP THE OPTIMAL ROLES OF MAN
NASA AMES
APRIL 1, 1964